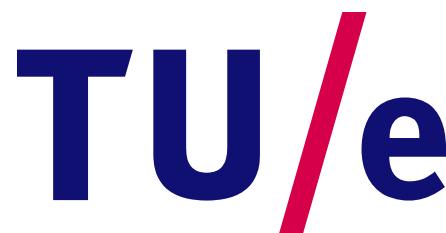


# **Generation of intense THz pulses using ultra-short, high-brightness electron bunches**

Jom Luiten



Technische Universiteit  
**Eindhoven**  
University of Technology

# Coherence & Quantum Technology (CQT)

**Willem Op 't Root – *PhD student***

**Peter Smorenburg – *PhD student***

**Bas van der Geer – *Pulsar Physics (GPT)***

**Marieke de Loos – *Pulsar Physics (GPT)***

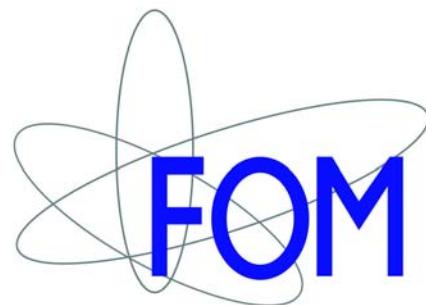
**Marnix van der Wiel – *former group leader***

***Technical support:***

**Eddy Rietman**

**Ad Kemper**

**Harry van Doorn**

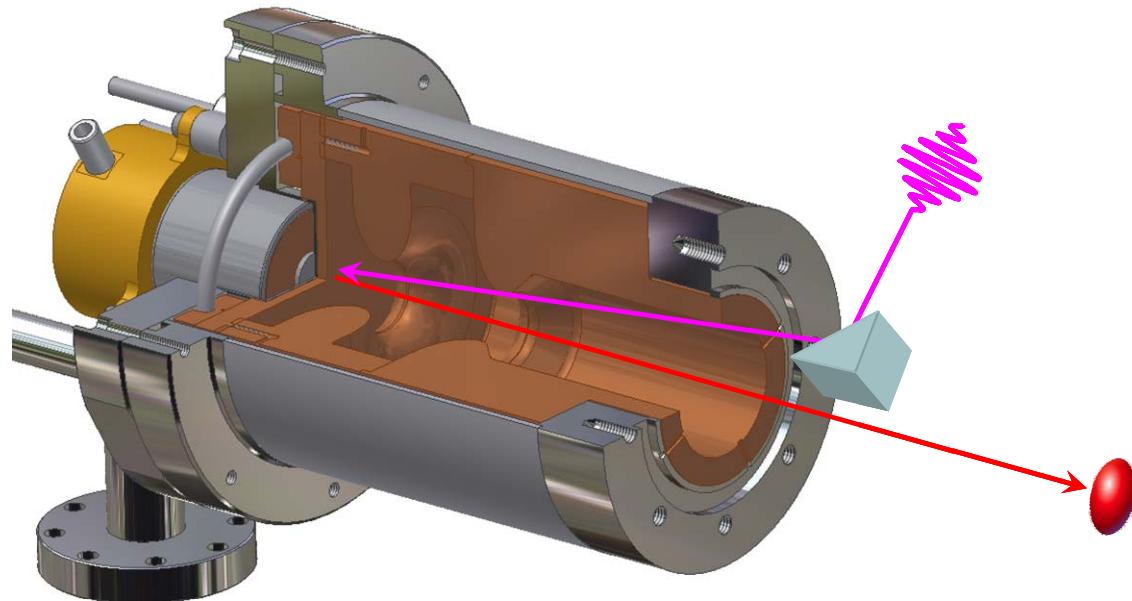


NL Foundation for Fundamental  
Research on Matter

# Outline

## Part I: RF photogun

- *technology*
- *ultra-short bunches*



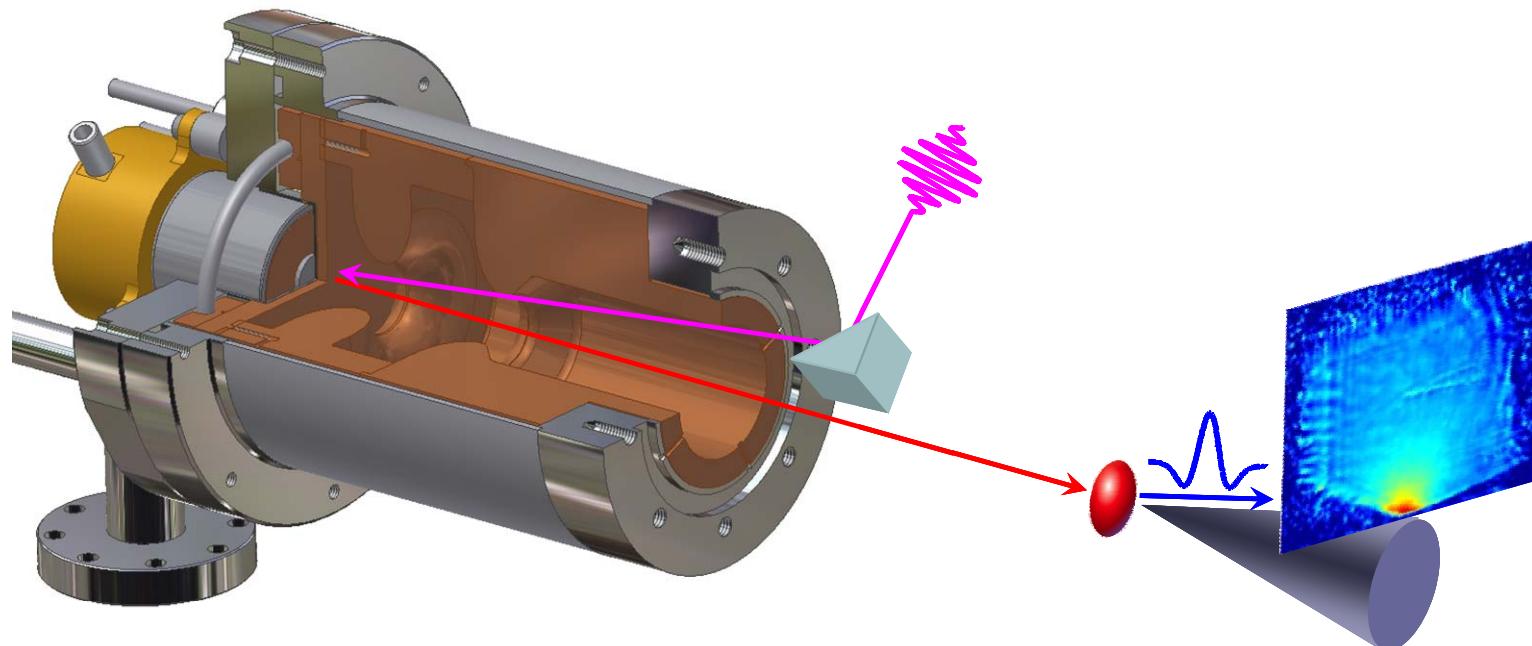
# Outline

## Part I: RF photogun

- *technology*
- *ultra-short bunches*

## Part II: THz generation

- *free-space CTR THz*
- *THz plasmons on a wire*



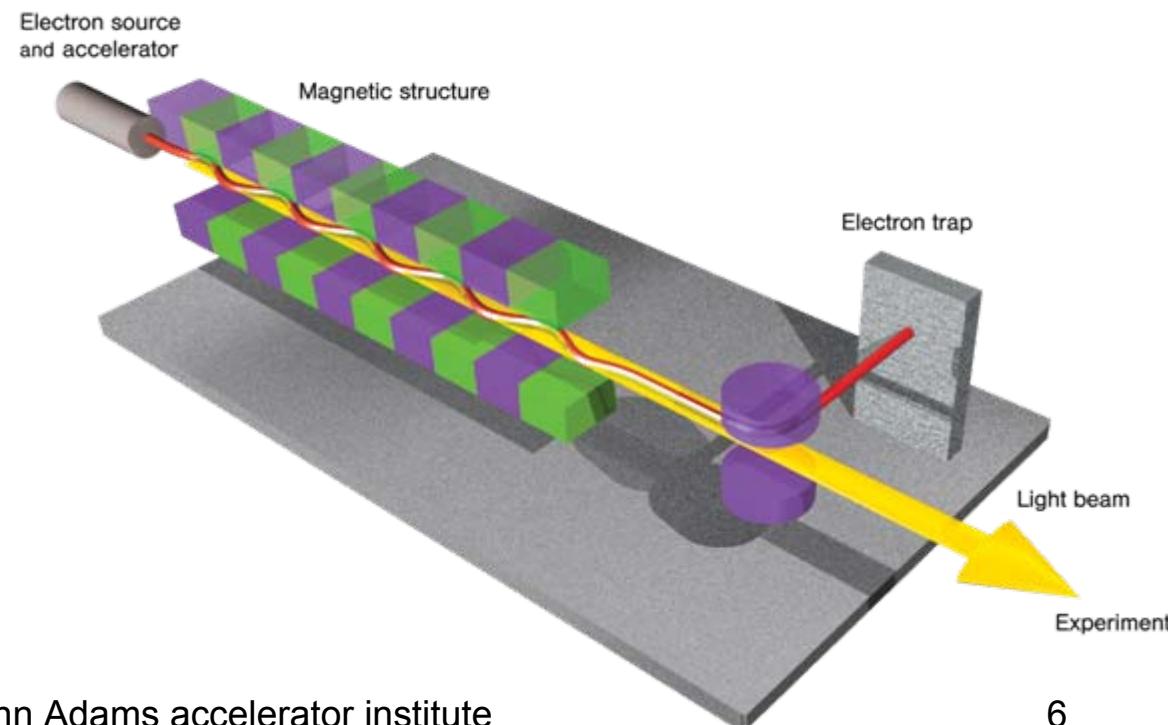
# Part I: RF photogun

# RF photoguns: the brightest pulsed electron sources...

- $U = 3\text{-}5 \text{ MeV}$
  - $Q = 0.1\text{-}1 \text{ nC}$
  - $\tau \leq 1 \text{ ps}$
  - $\epsilon_n \leq 1 \text{ mm}\cdot\text{mrad}$
- $I = 0.1\text{-}1 \text{ kA}$

Injector X-FEL...

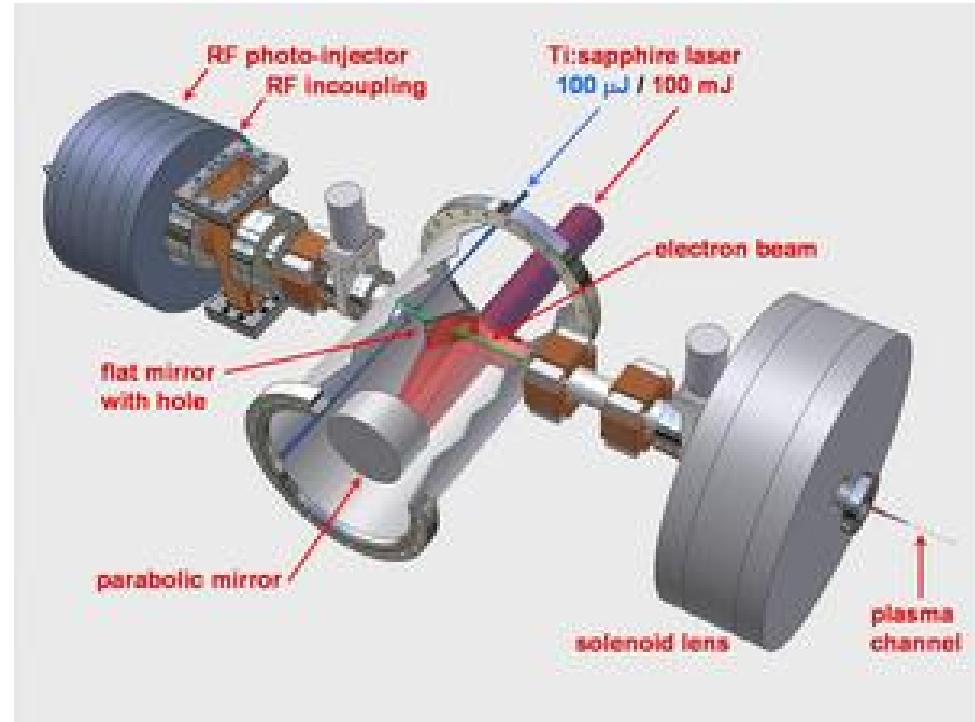
*SLAC, DESY, ...*



# RF photoguns: the brightest pulsed electron sources...

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  - $Q = 0.1\text{-}1 \text{ nC}$
  - $\tau \leq 1 \text{ ps}$
  - $\epsilon_n \leq 1 \text{ mm}\cdot\text{mrad}$
- $I = 0.1\text{-}1 \text{ kA}$

...injector LWA...



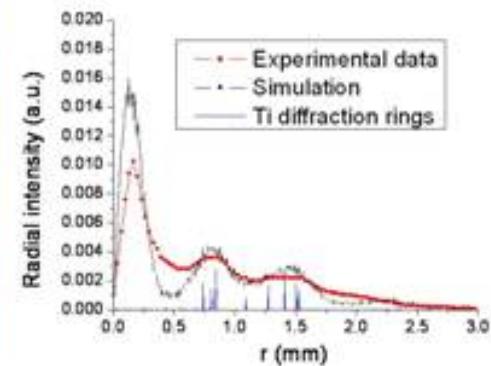
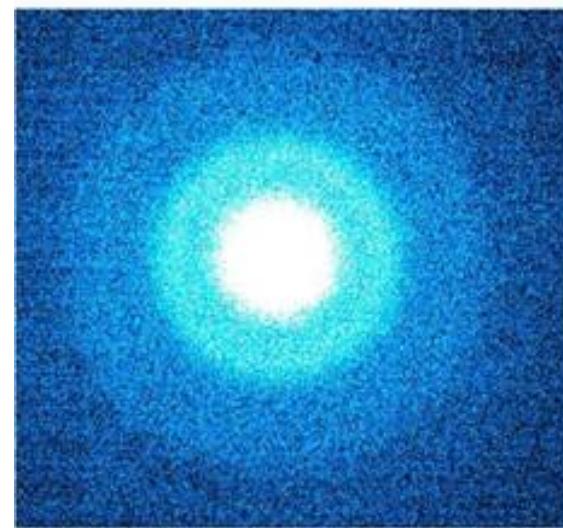
*TU/e, Strathclyde,  
EuroLeap...*

# RF photoguns: the brightest pulsed electron sources...

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  - $\epsilon_n \leq 1 \text{ mm}\cdot\text{mrad}$
- $I = 0.1\text{-}1 \text{ kA}$

...ultrafast electron  
diffraction...

**TU/e, UCLA, BNL, ...**



200 nm Ti foil, Musumeci et al., UCLA

# RF photoguns: the brightest pulsed electron sources...

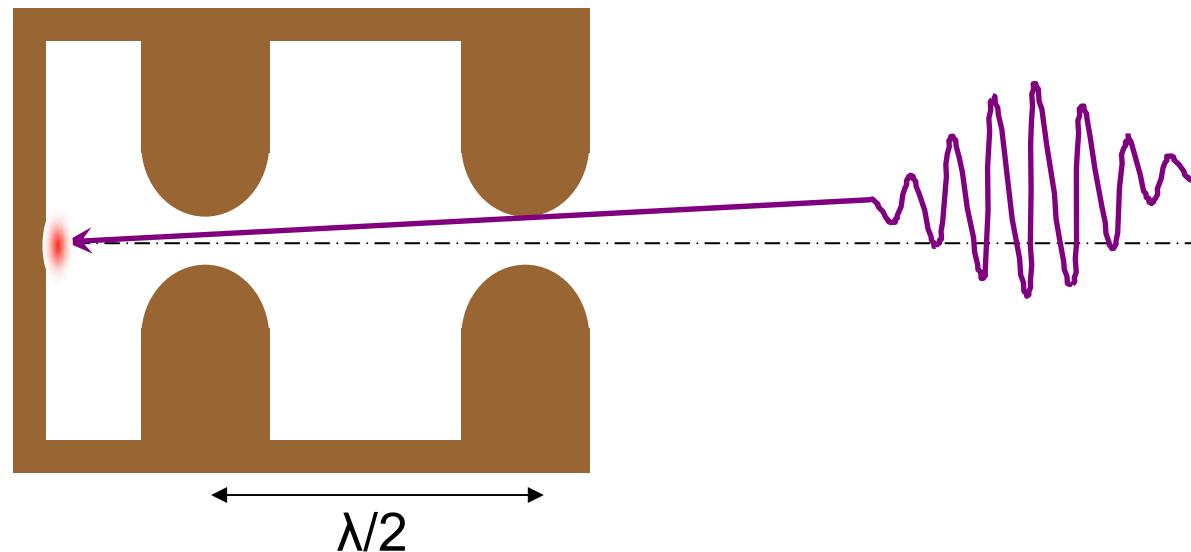
- $U = 3\text{-}5 \text{ MeV}$
  - $Q = 0.1\text{-}1 \text{ nC}$
  - $\tau \leq 1 \text{ ps}$
  - $\varepsilon_n \leq 1 \text{ mm}\cdot\text{mrad}$
- $I = 0.1\text{-}1 \text{ kA}$

... intense THz pulses.



# RF photoguns: the brightest pulsed electron sources...

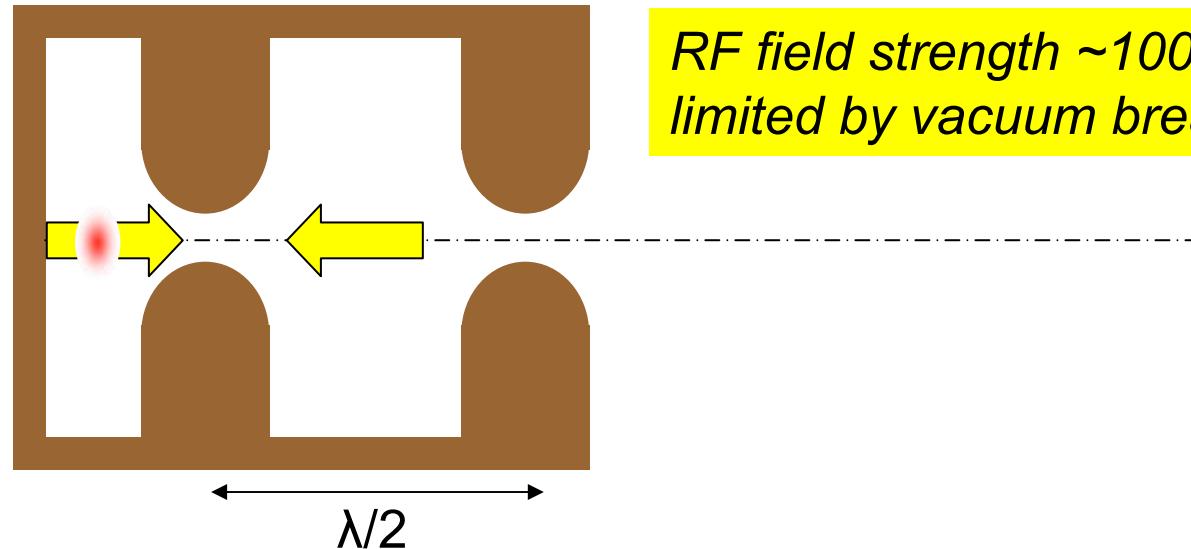
Pulsed laser photoemission...



3 GHz ( $\lambda=10$  cm) resonant cavity

# RF photoguns: the brightest pulsed electron sources...

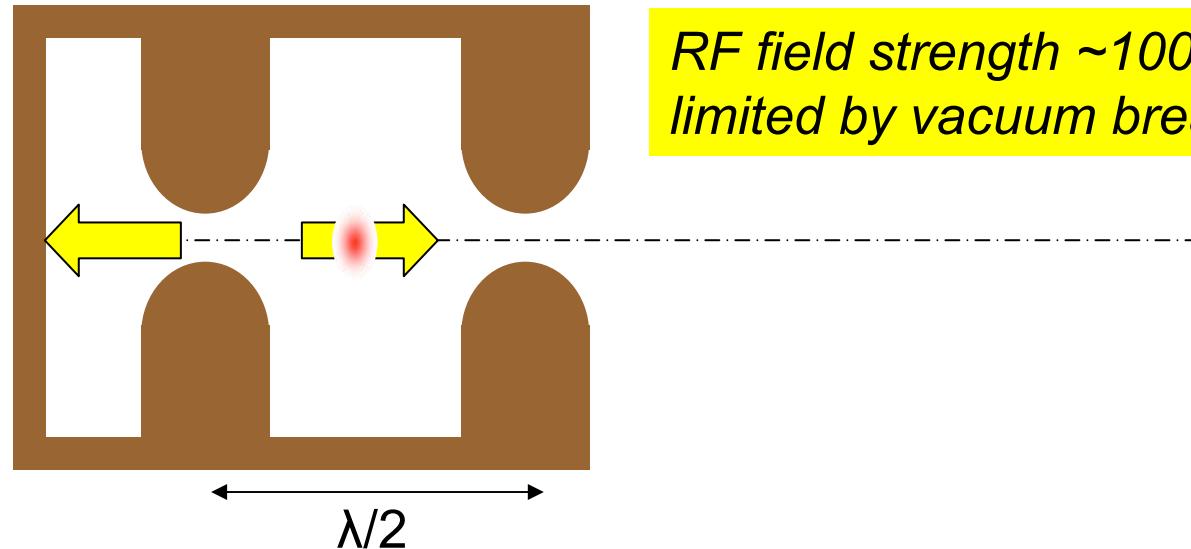
...and RF acceleration.



3 GHz ( $\lambda=10 \text{ cm}$ ) resonant cavity

# RF photoguns: the brightest pulsed electron sources...

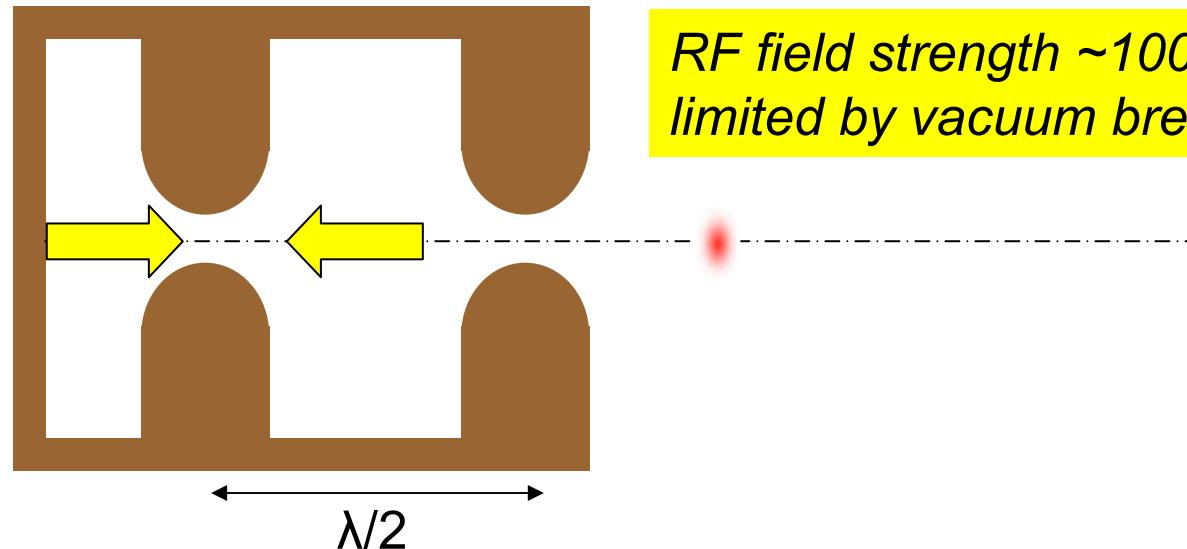
...and RF acceleration.



3 GHz ( $\lambda=10$  cm) resonant cavity

# RF photoguns: the brightest pulsed electron sources...

...and RF acceleration.

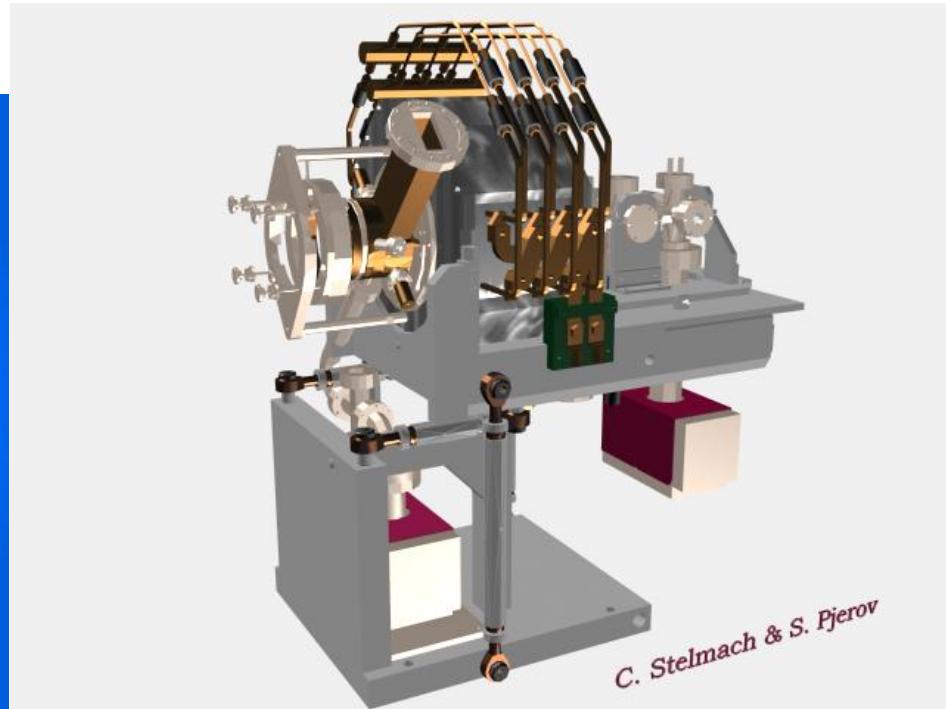


*RF field strength  $\sim 100 \text{ MV/m}$ ,  
limited by vacuum breakdown*

3 GHz ( $\lambda=10 \text{ cm}$ ) resonant cavity

# RF photoguns: the brightest pulsed electron sources...

ATF-BNL-UCLA 1.6 cell photogun



# TU/e approach:

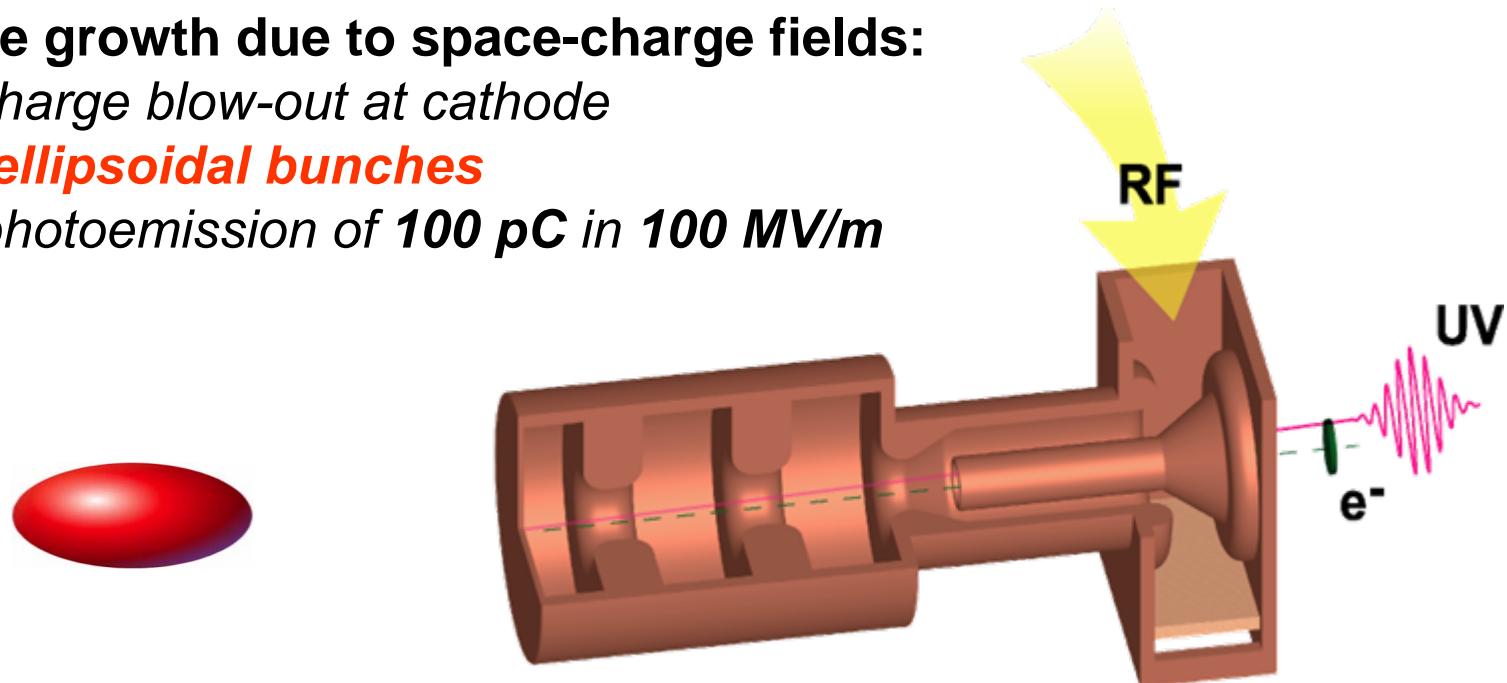
Emittance growth due to non-linear acceleration fields:

- *full cylindrical symmetry*
- *no tuning plungers*
- *on-axis RF coupling*

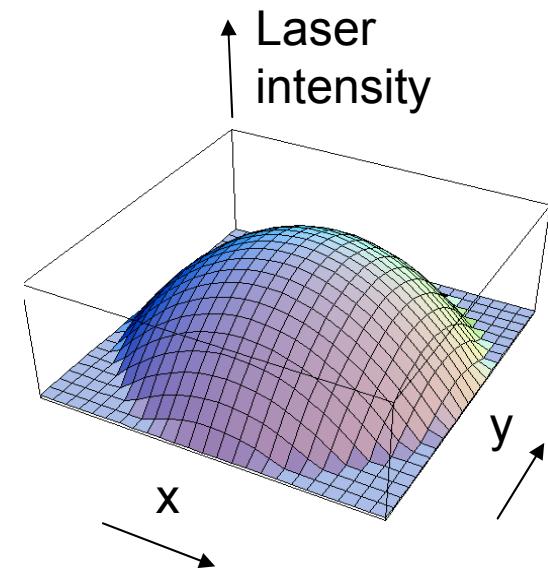
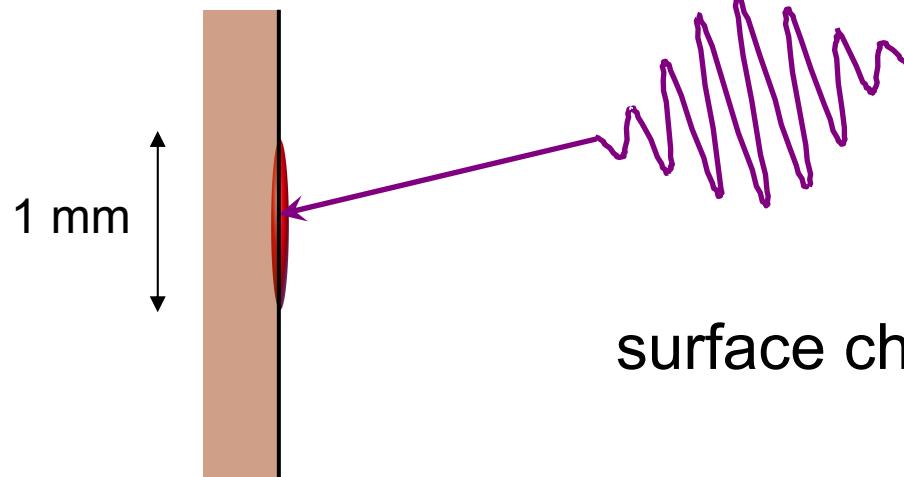
*single-diamond turning*

Emittance growth due to space-charge fields:

- space-charge blow-out at cathode
- *ideally: ellipsoidal bunches*
- *100 fs photoemission of 100 pC in 100 MV/m*



# *Shaped fs laser pulse...*



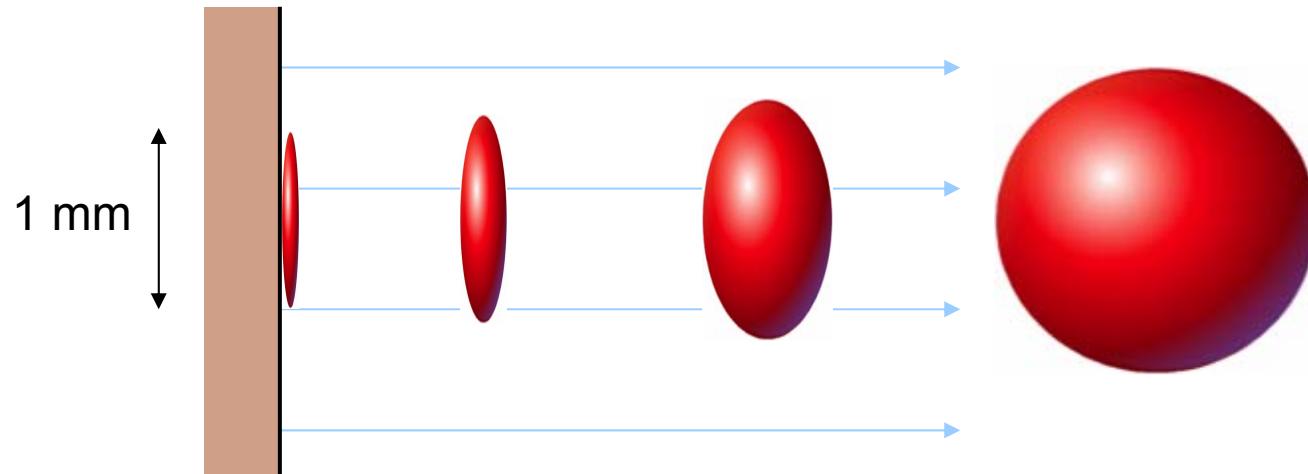
surface charge density distribution:

$$\sigma(r) = \sigma_0 \sqrt{1 - (r/R)^2}$$

Luiten et al., PRL **93**, 094802 (2004)

...evolution into *uniform ellipsoid*.

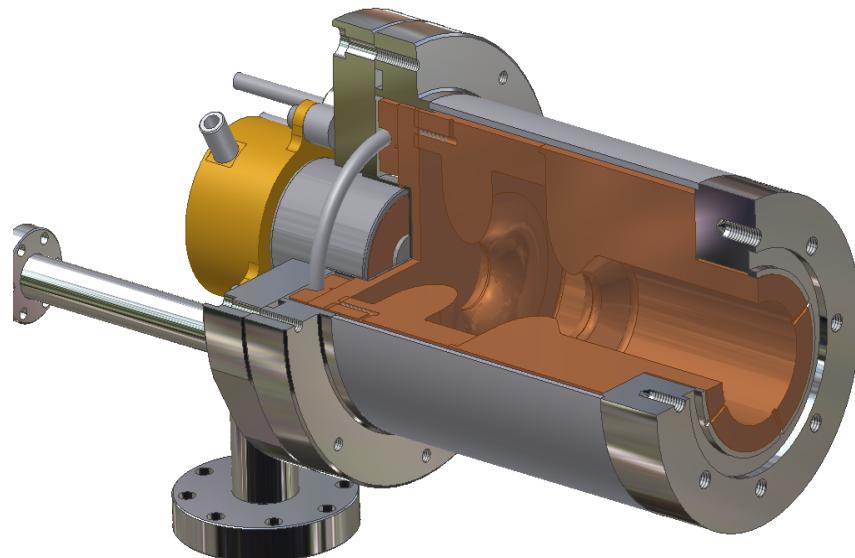
→ *linear & reversible* Coulomb expansion



Luiten et al., PRL **93**, 094802 (2004)

# 2nd generation TU/e gun:

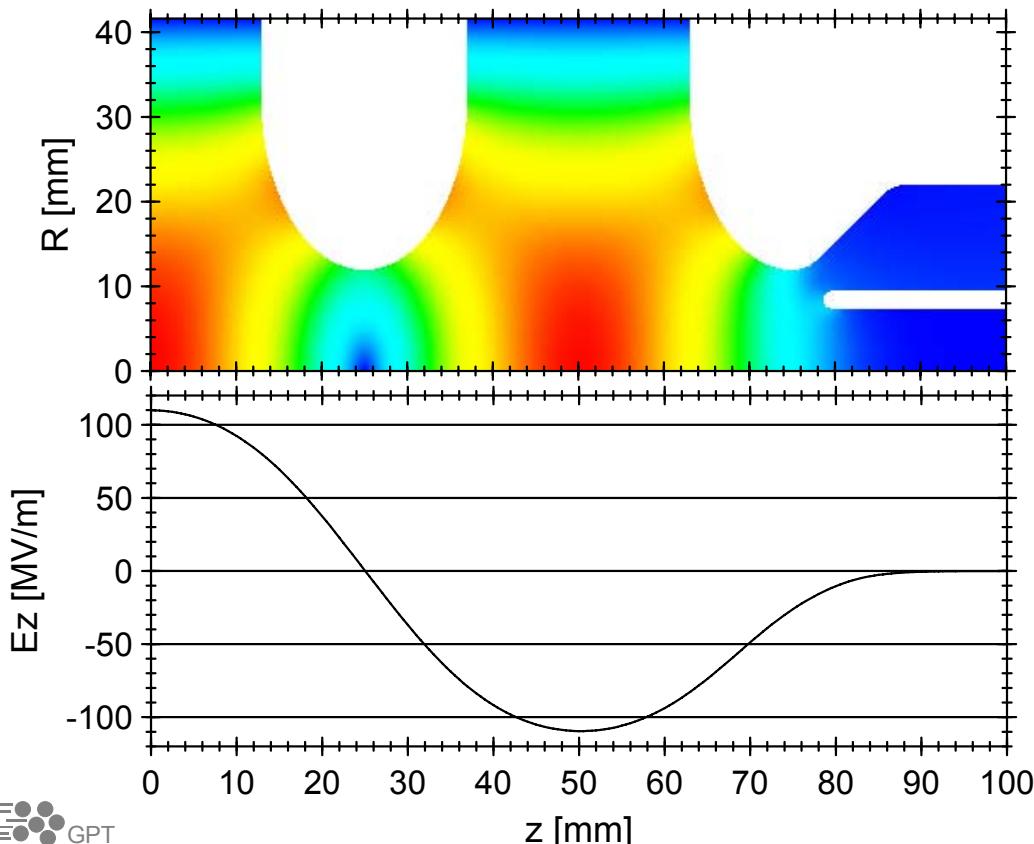
- Elliptical irises
  - *Highest field strength on cathode;*
- Cavity parts are clamped, not braized
  - *Easily replaced;*
- Copper cavity inside stainless vacuum can.



# 2nd generation TU/e gun:

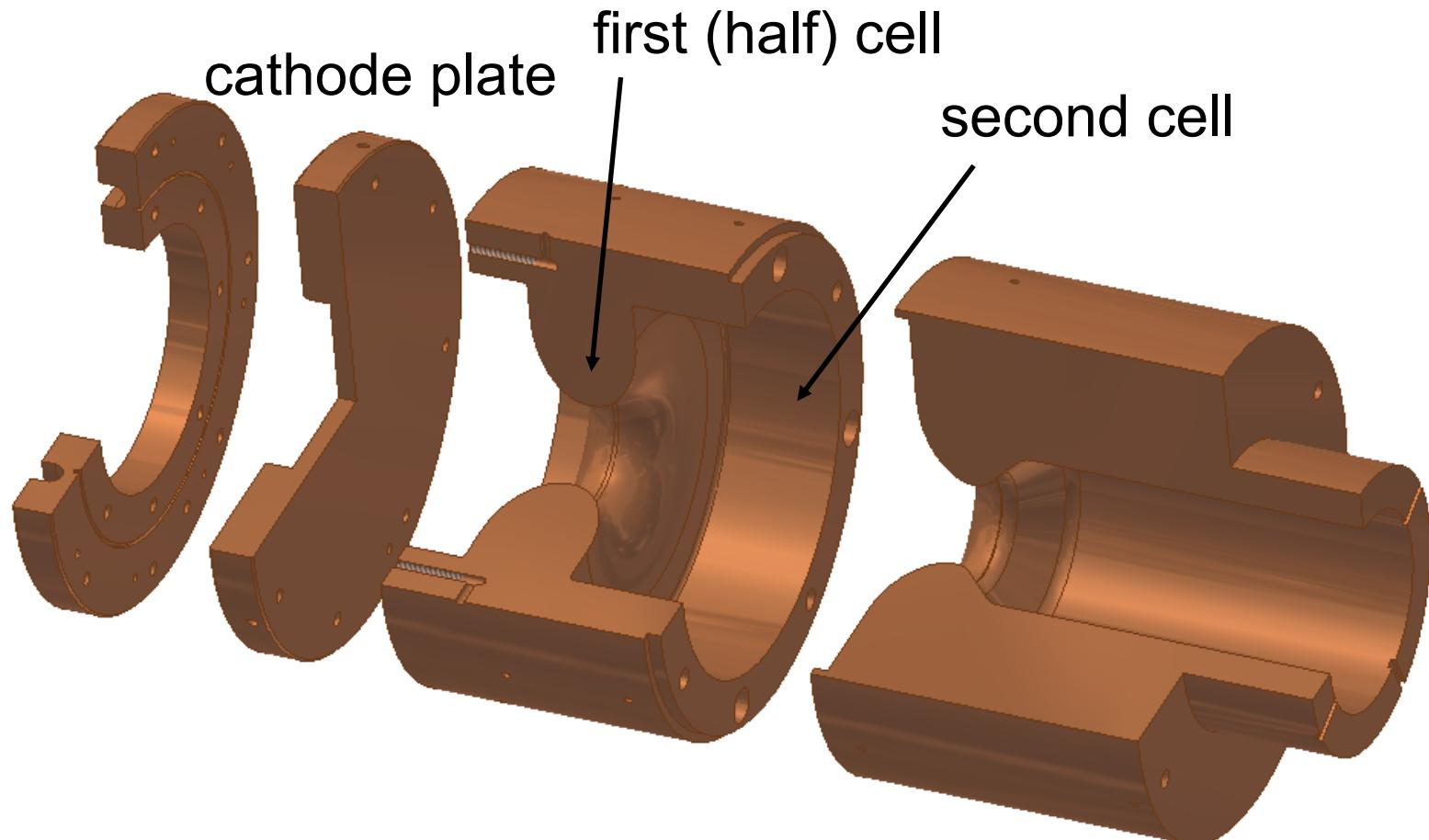
Elliptical irises:

*Highest field strength on cathode*



# 2nd generation TU/e gun:

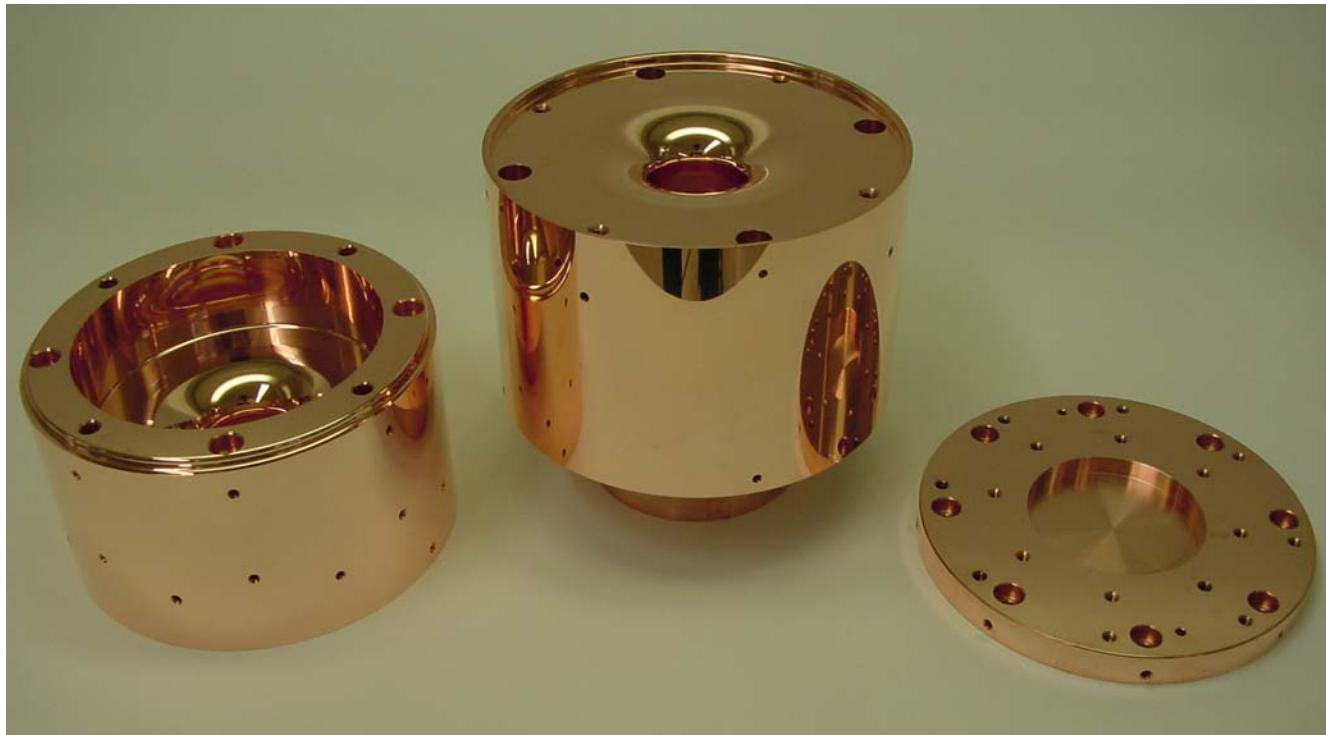
Clamped construction:  
*cavity parts*



# 2nd generation TU/e gun:

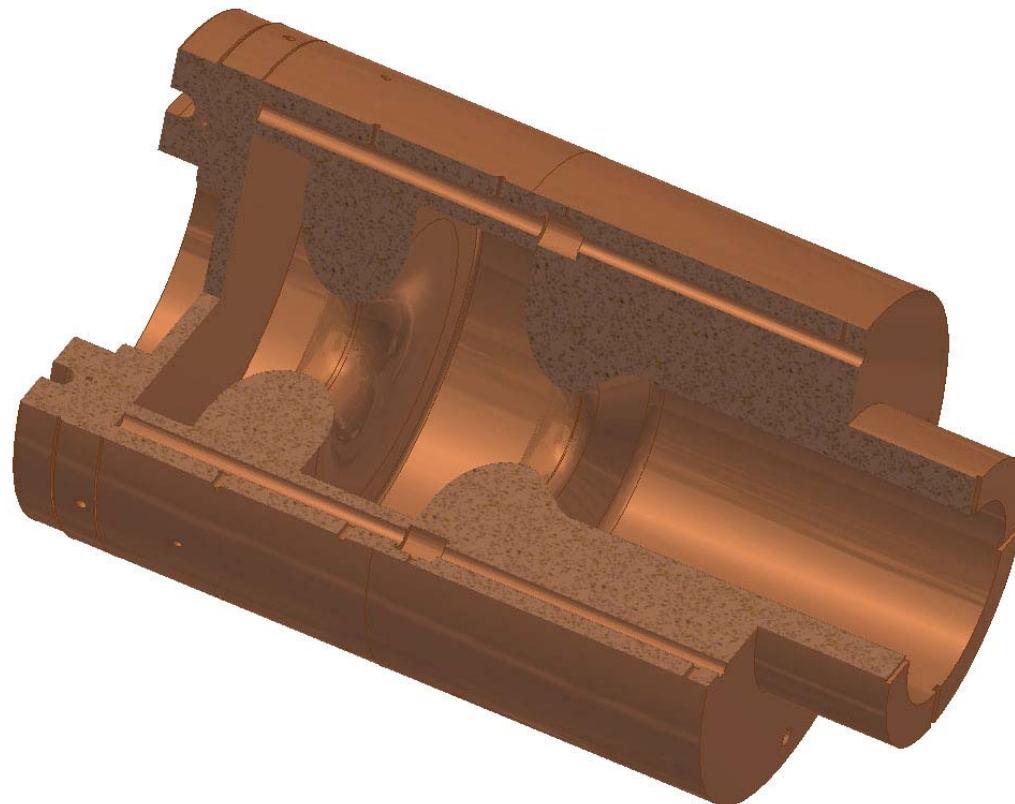
Clamped construction:  
*cavity parts*

*single-diamond turning*



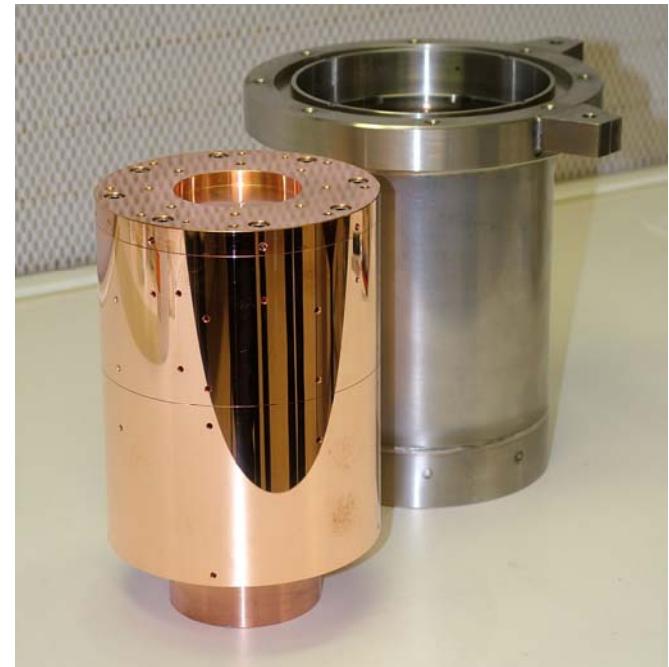
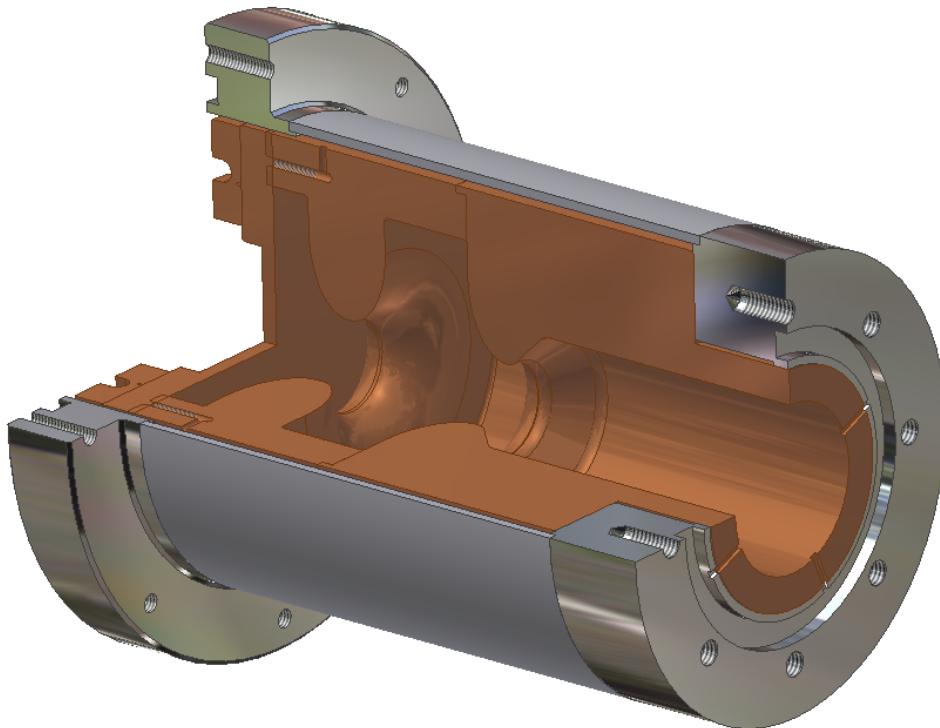
# 2nd generation TU/e gun:

Clamped construction:  
*assembled cavity parts*



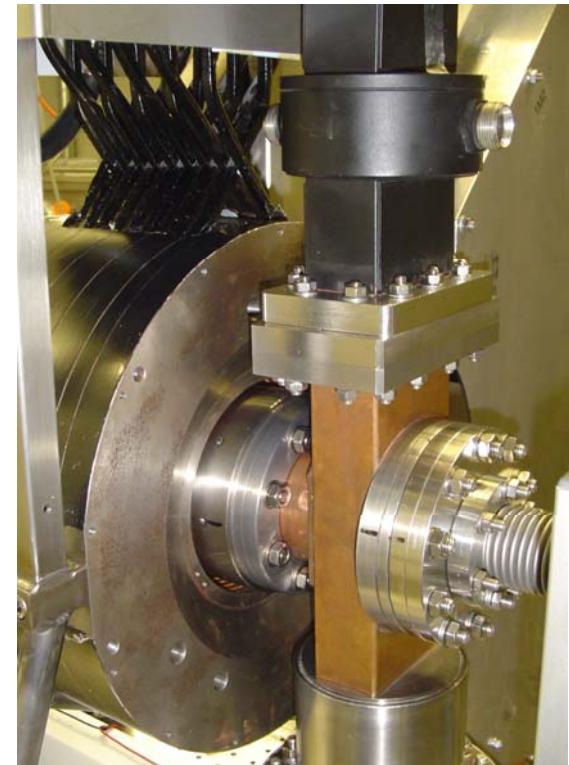
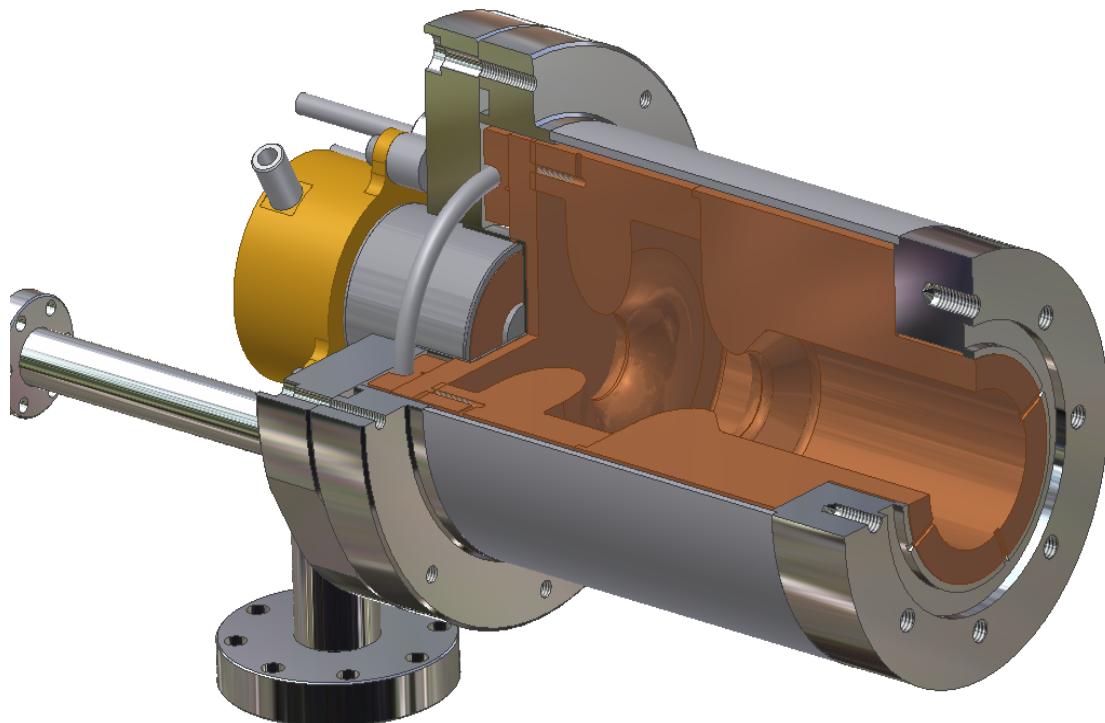
# 2nd generation TU/e gun:

Clamped construction:  
*cavity inside stainless steel vacuum can*



# 2nd generation TU/e gun:

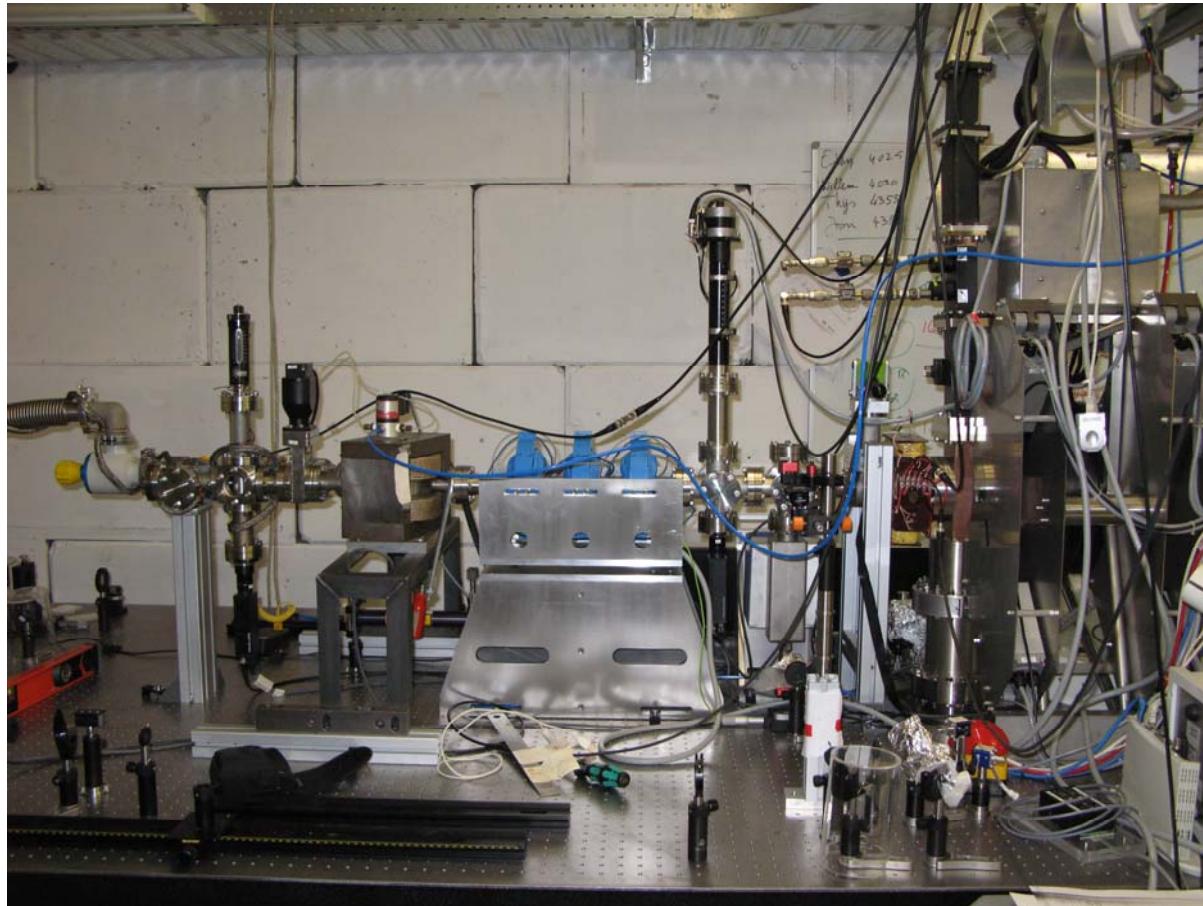
Assembled gun:



Solenoid around cavity

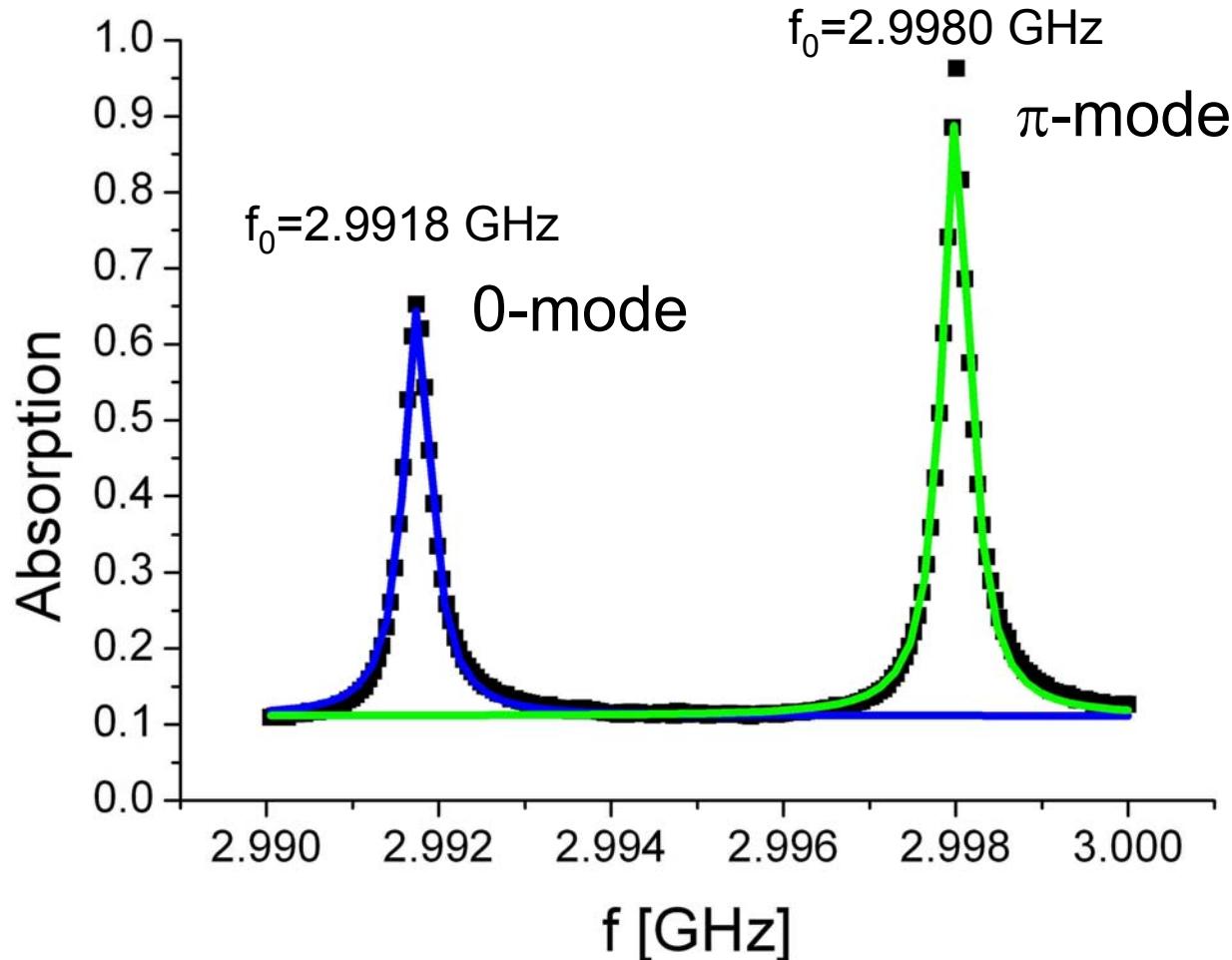
# 2nd generation TU/e gun:

Entire setup: *gun & beamline*



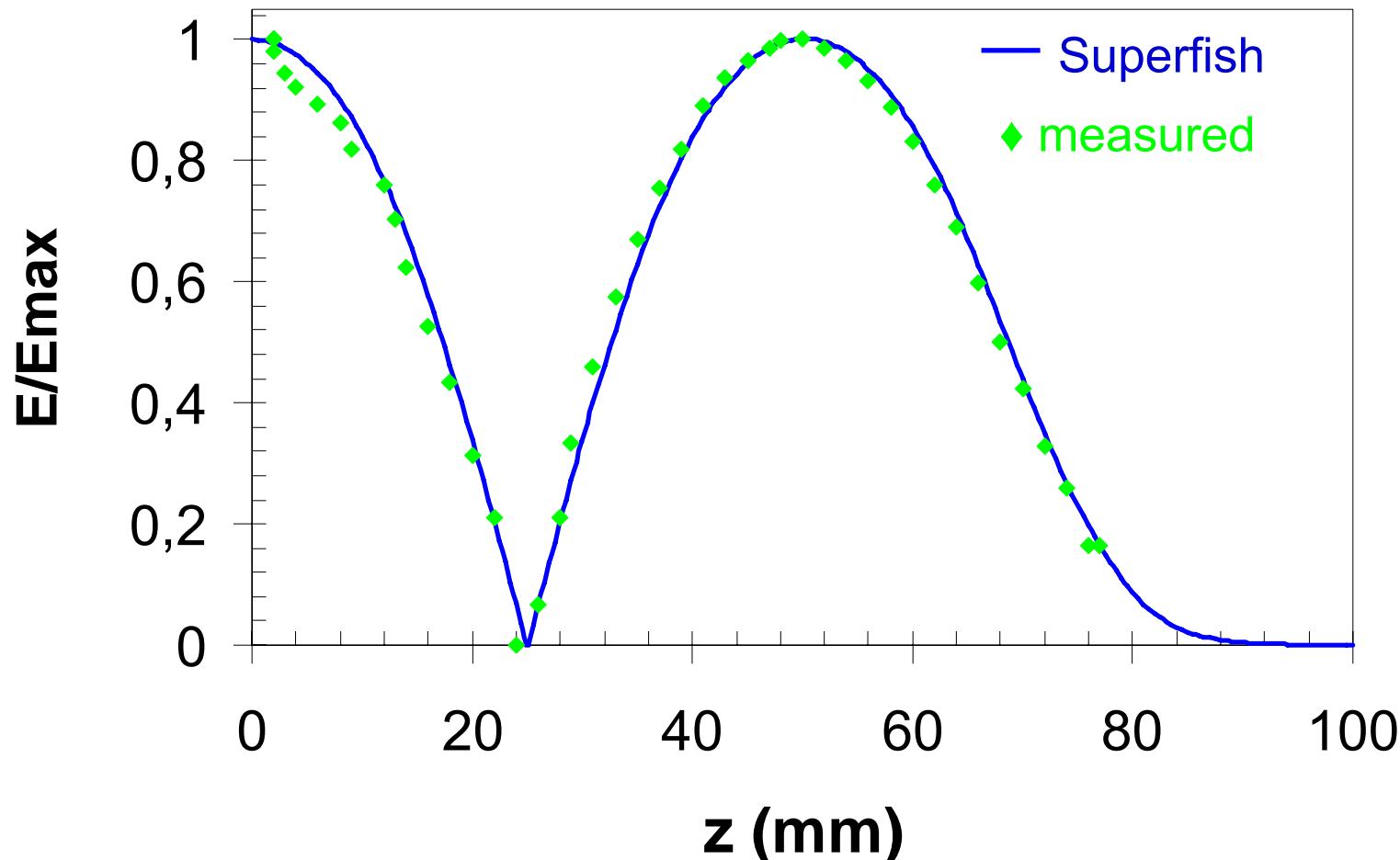
# 2nd generation TU/e gun:

RF characterization: *resonances*



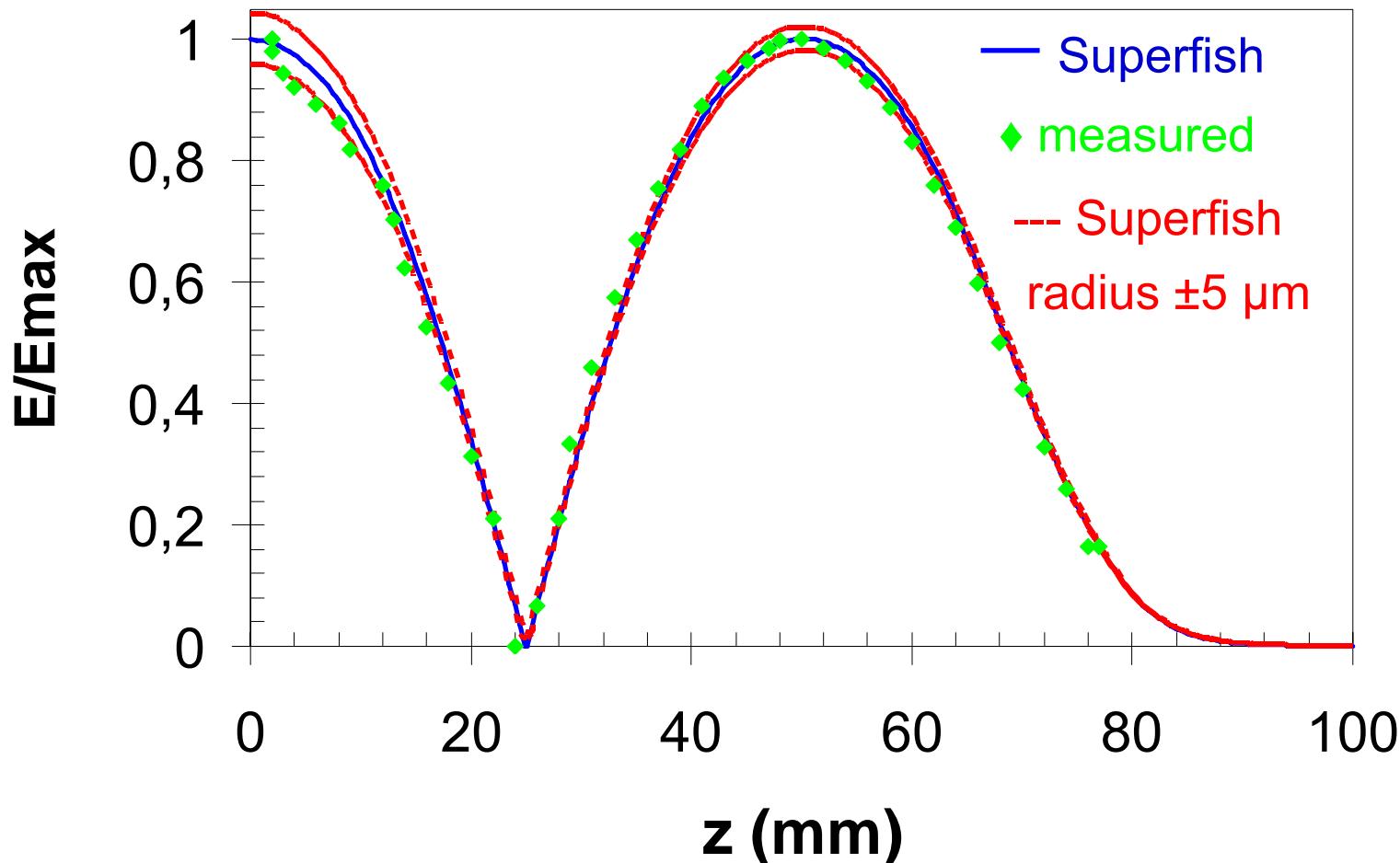
# 2nd generation TU/e gun:

RF characterization: *on axis field profile*



# 2nd generation TU/e gun:

RF characterization: *on axis field profile*



# 2nd generation TU/e gun:

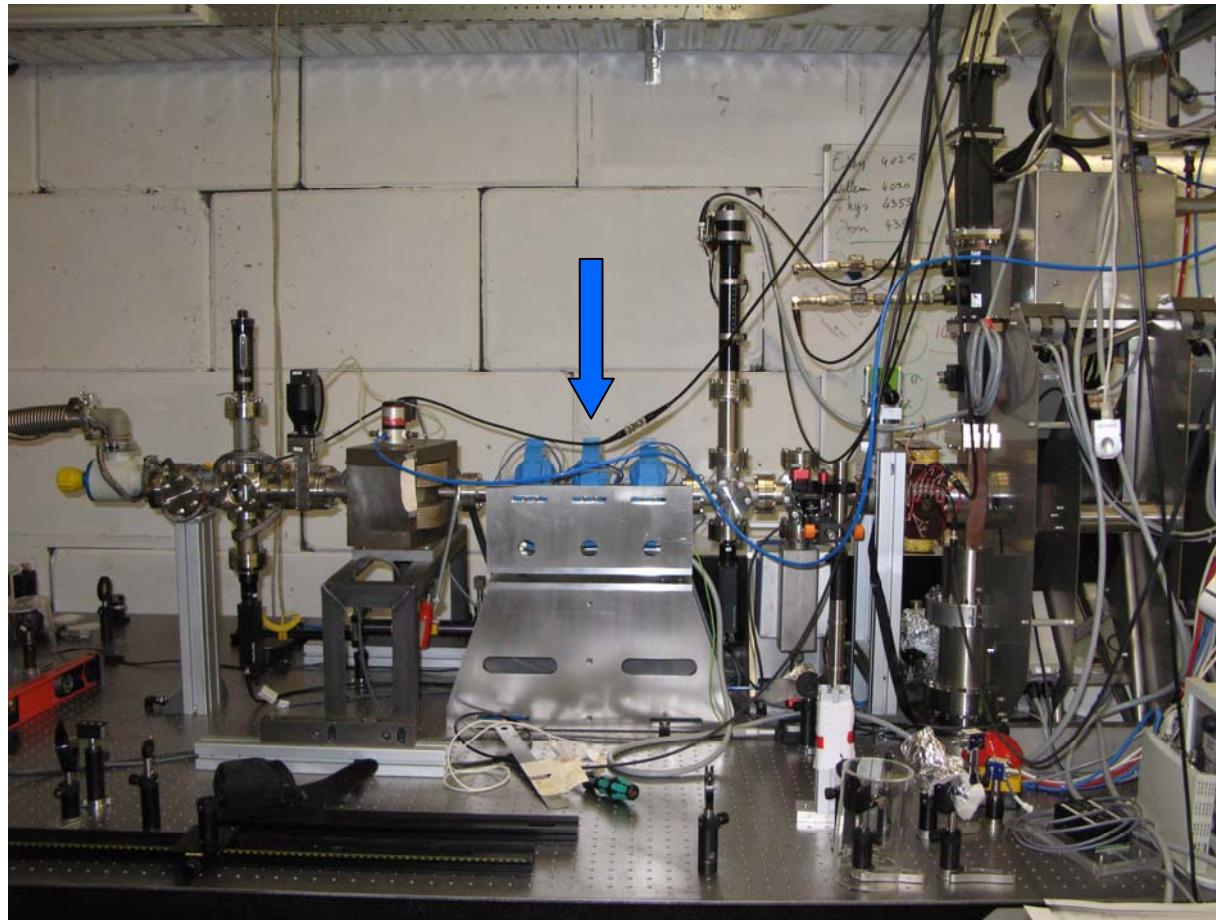
High power RF commissioning:

- *80 MV/m at cathode (after one month of training)*
- *Still occasional breakdown*
- *3 MeV electrons*
- $QE \approx 3 \cdot 10^{-5} \rightarrow \text{bunch charge } Q_{max} \approx 300 \text{ pC}$

**Conclusion: clamping is OK!**

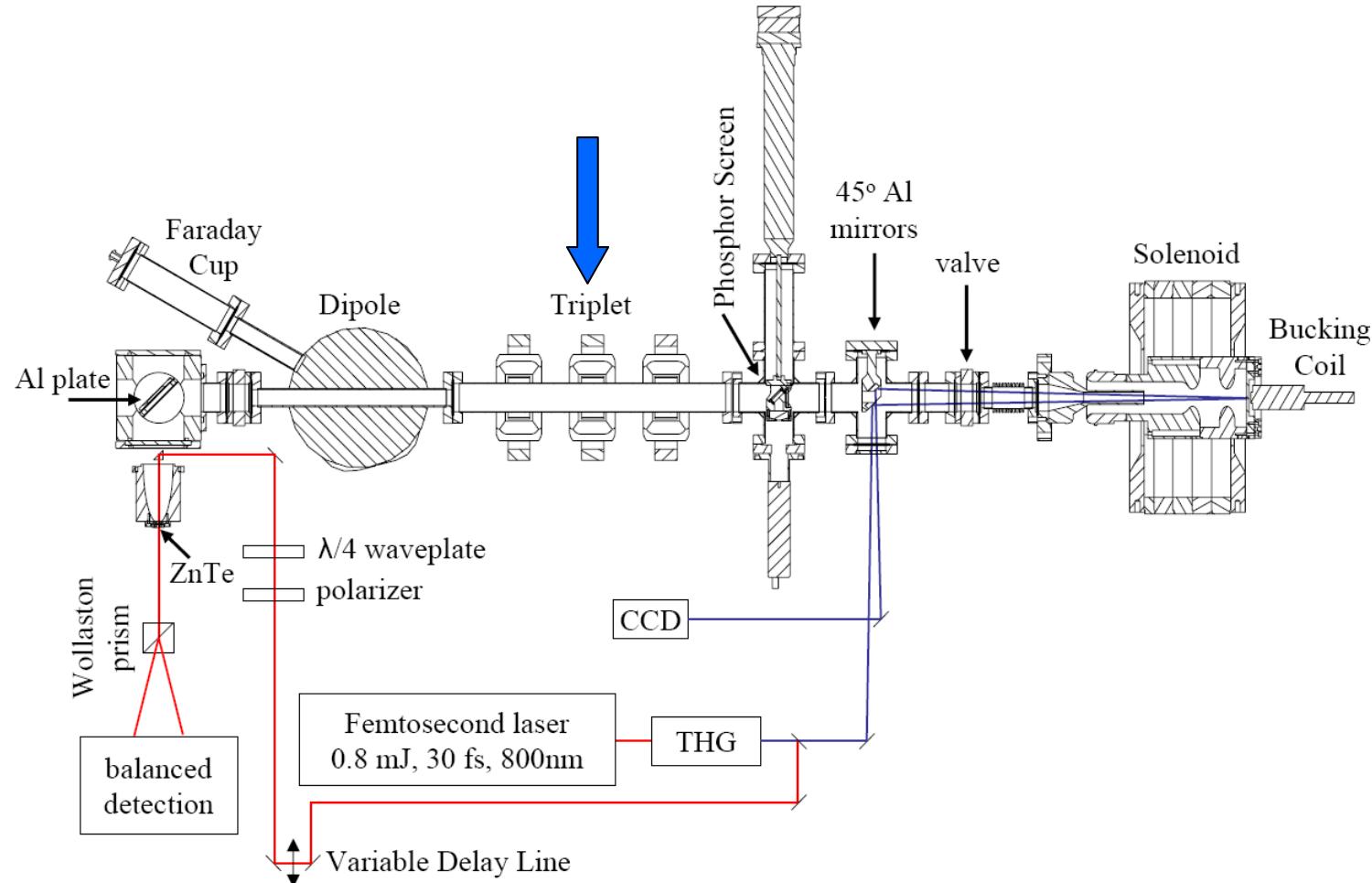
# Emittance measurement:

Quadrupole scan:



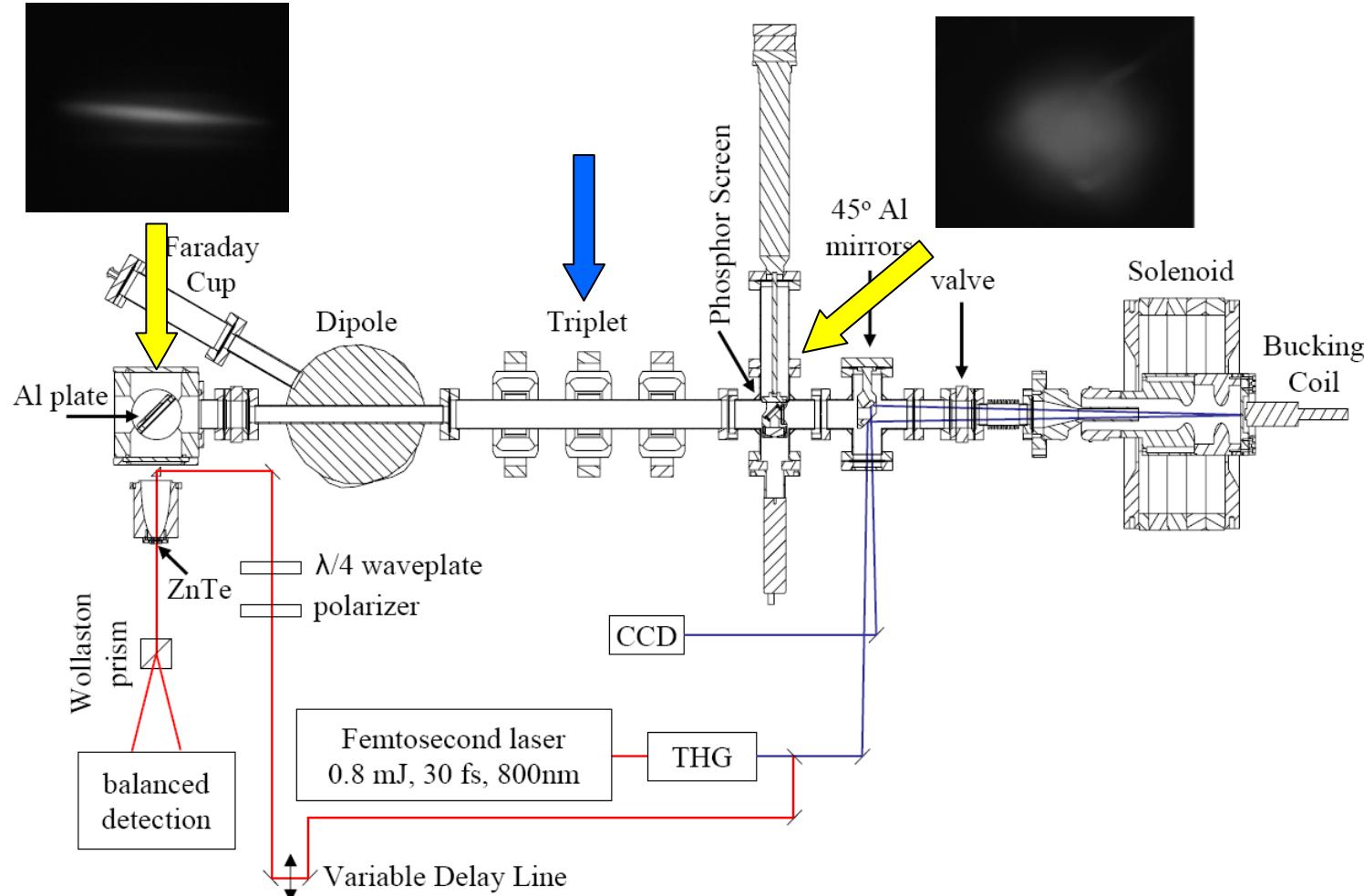
# Emittance measurement:

Quadrupole scan:



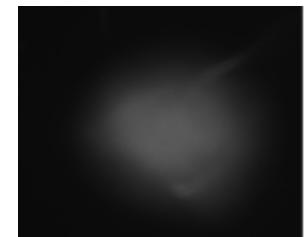
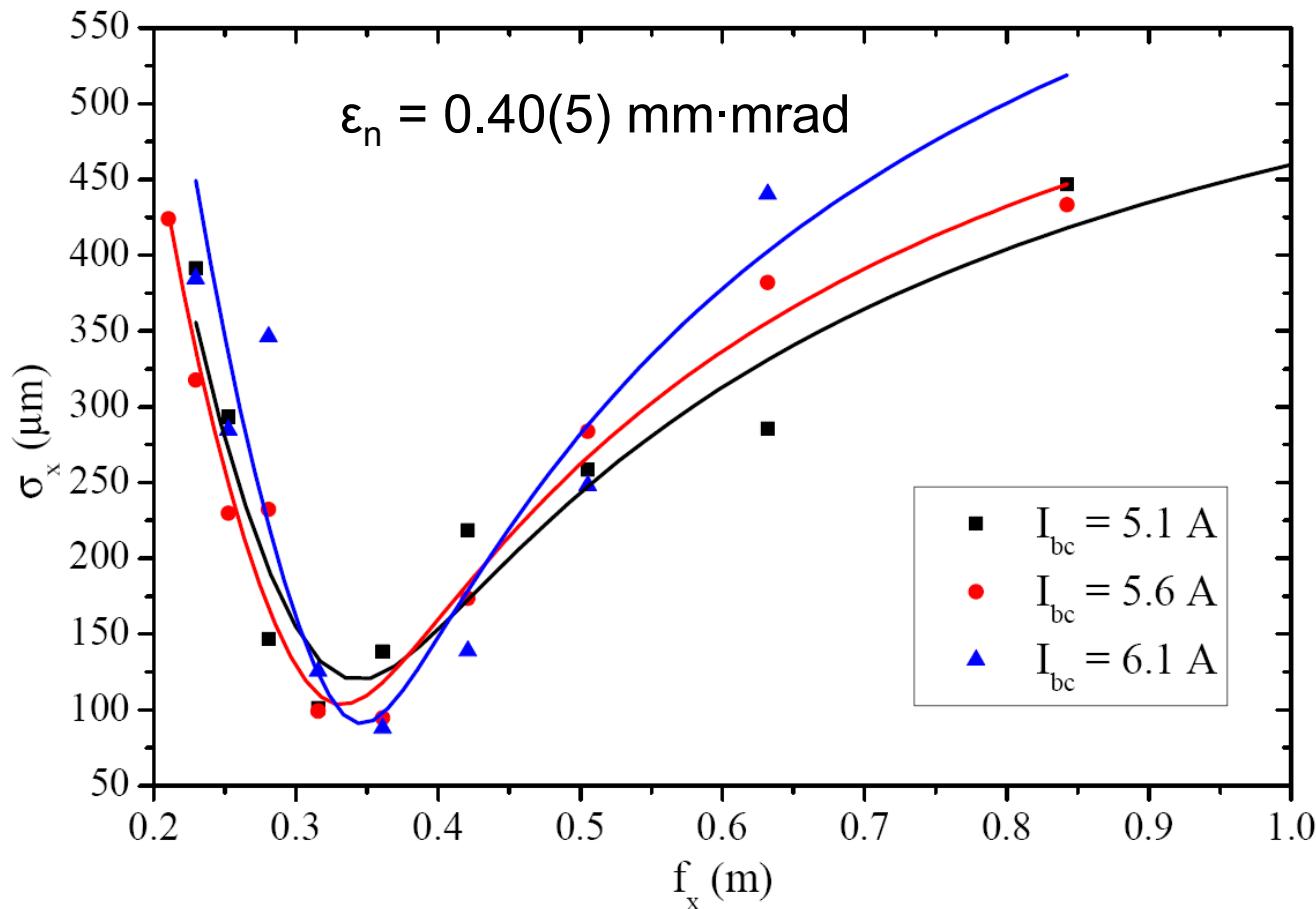
# Emittance measurement:

Quadrupole scan:



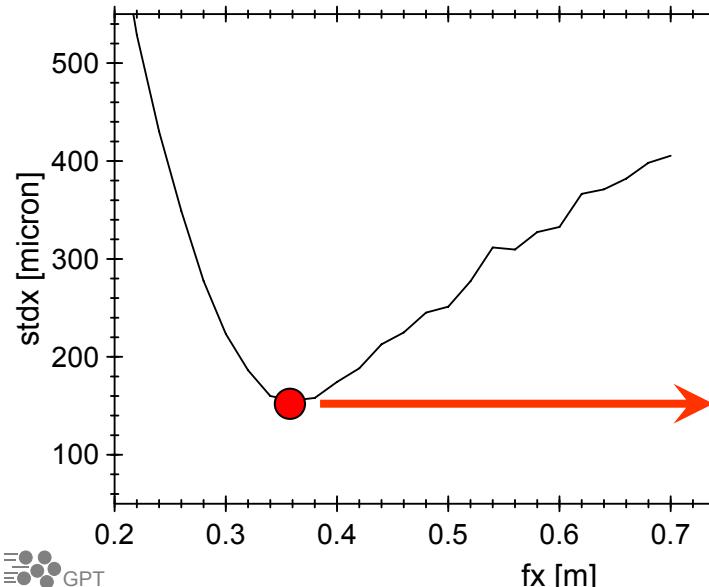
# Emittance measurement:

Quadrupole scan:  $Q = 5 \text{ pC}$



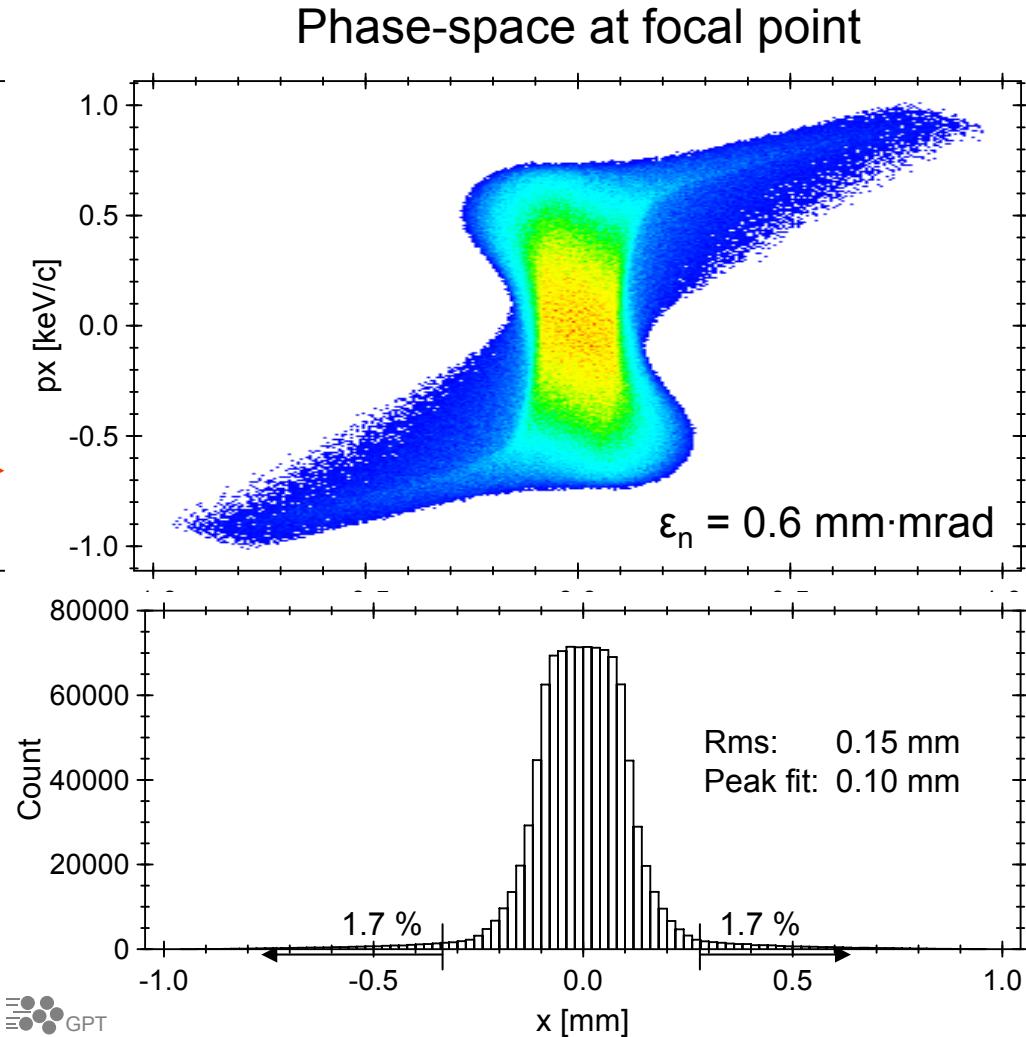
# Emittance GPT simulation:

Quadrupole scan:  $Q = 5 \text{ pC}$ ,  $10^6 \text{ particles}$



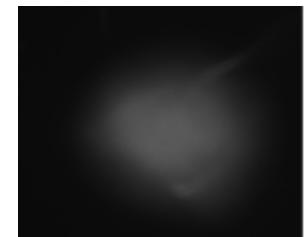
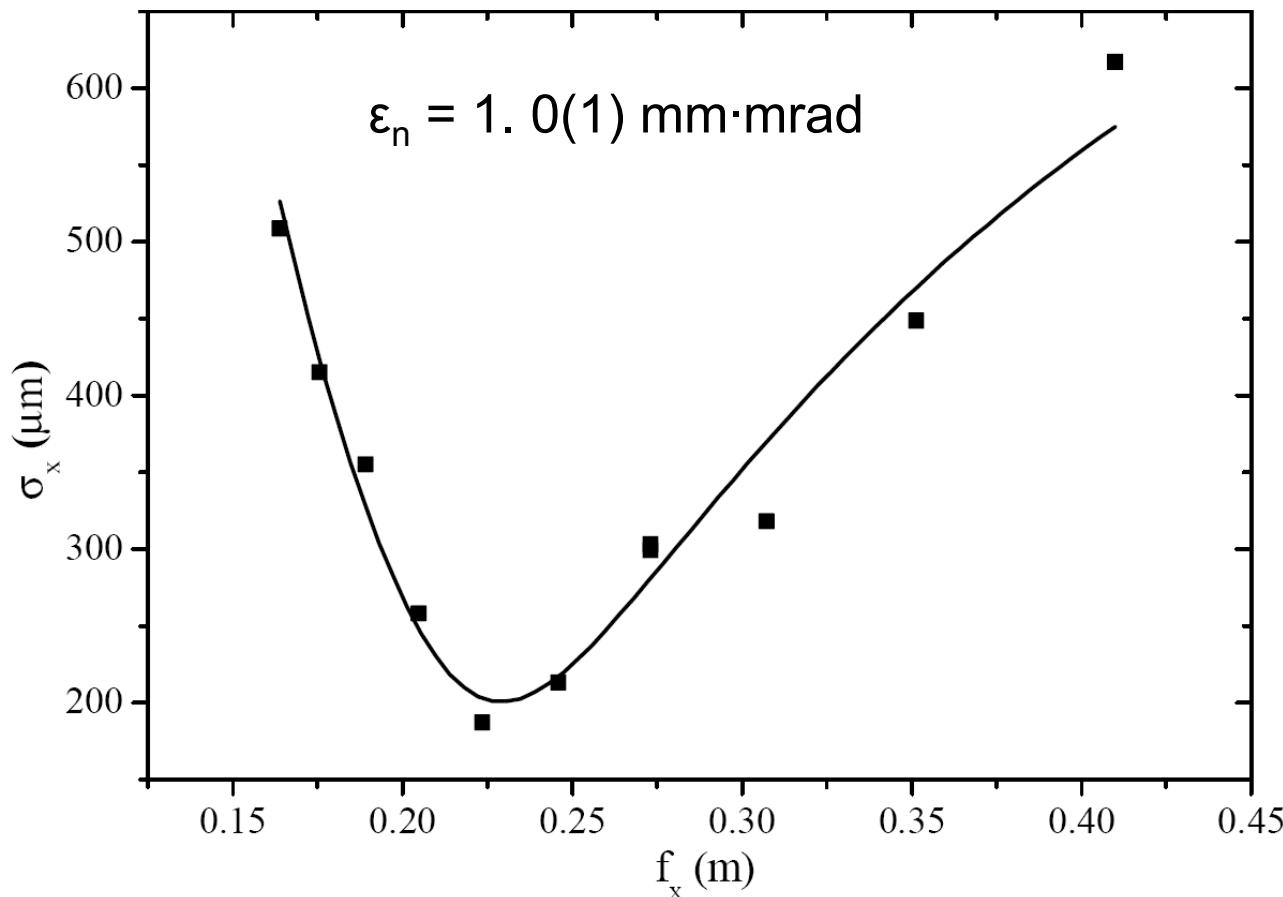
- very good agreement
- still space-charge dominated

8 Oct 2009



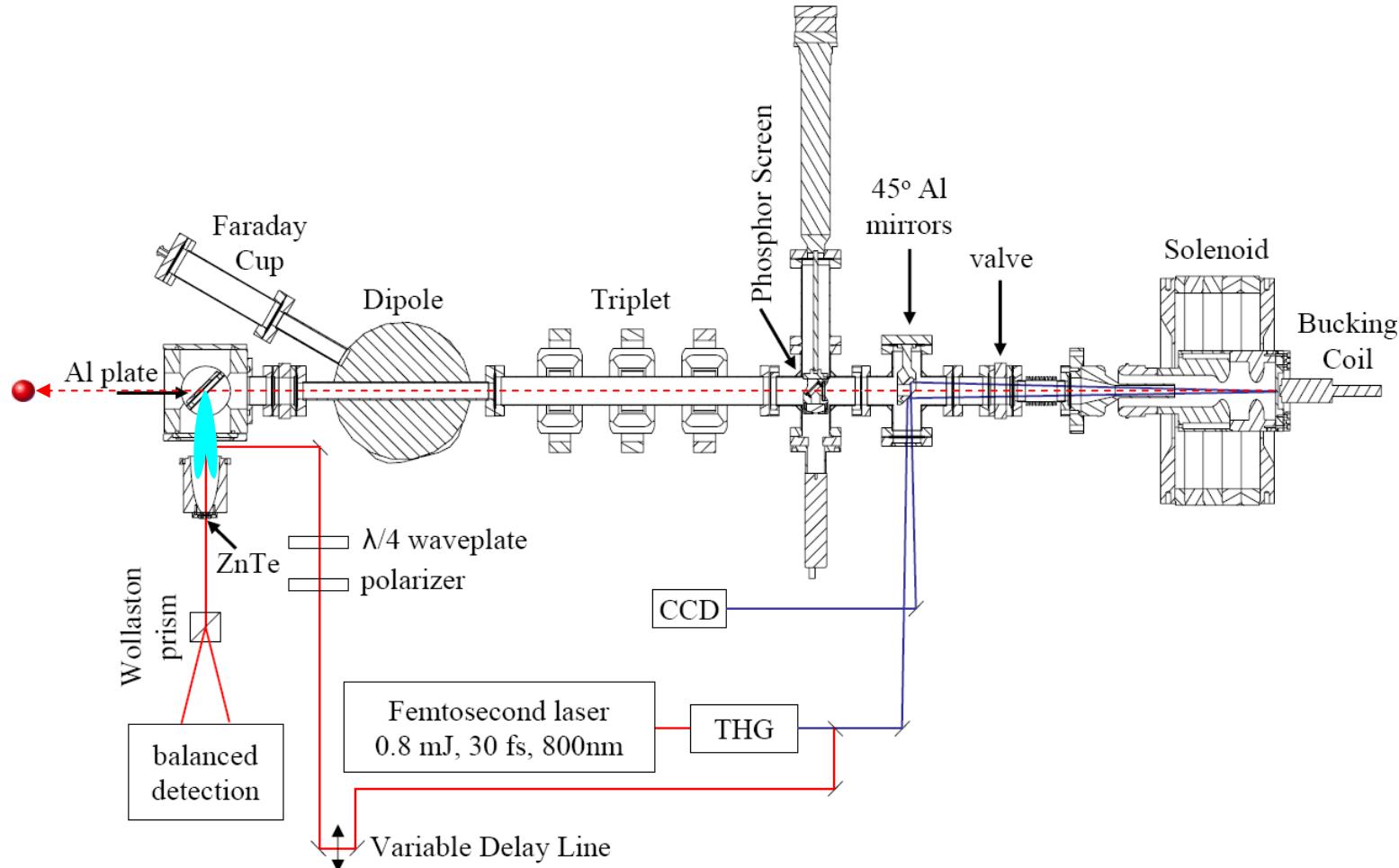
# Emittance measurement:

Quadrupole scan:  $Q = 70 \text{ pC}$



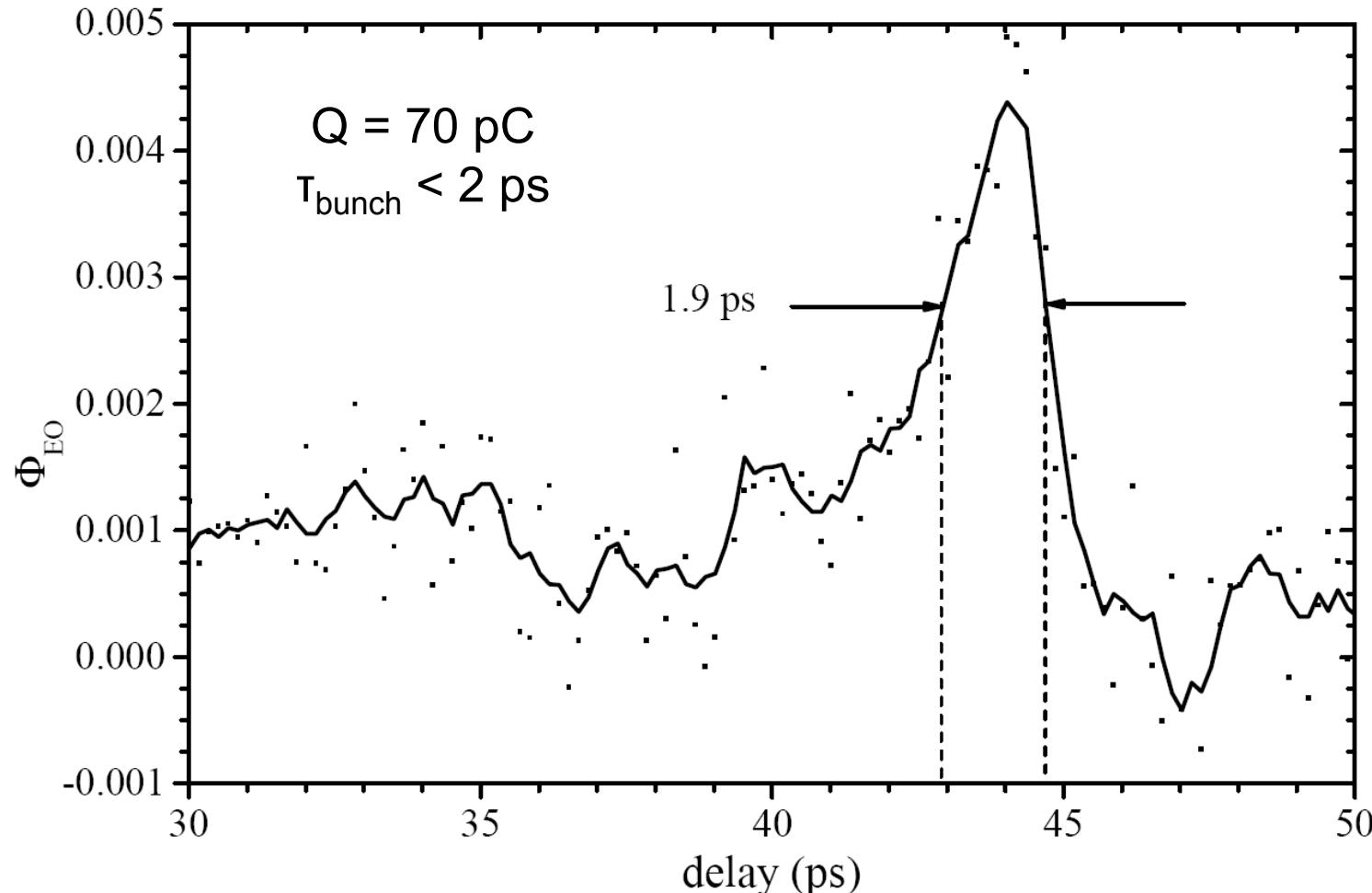
# Bunch length measurement:

## Coherent Transition Radiation (CTR)



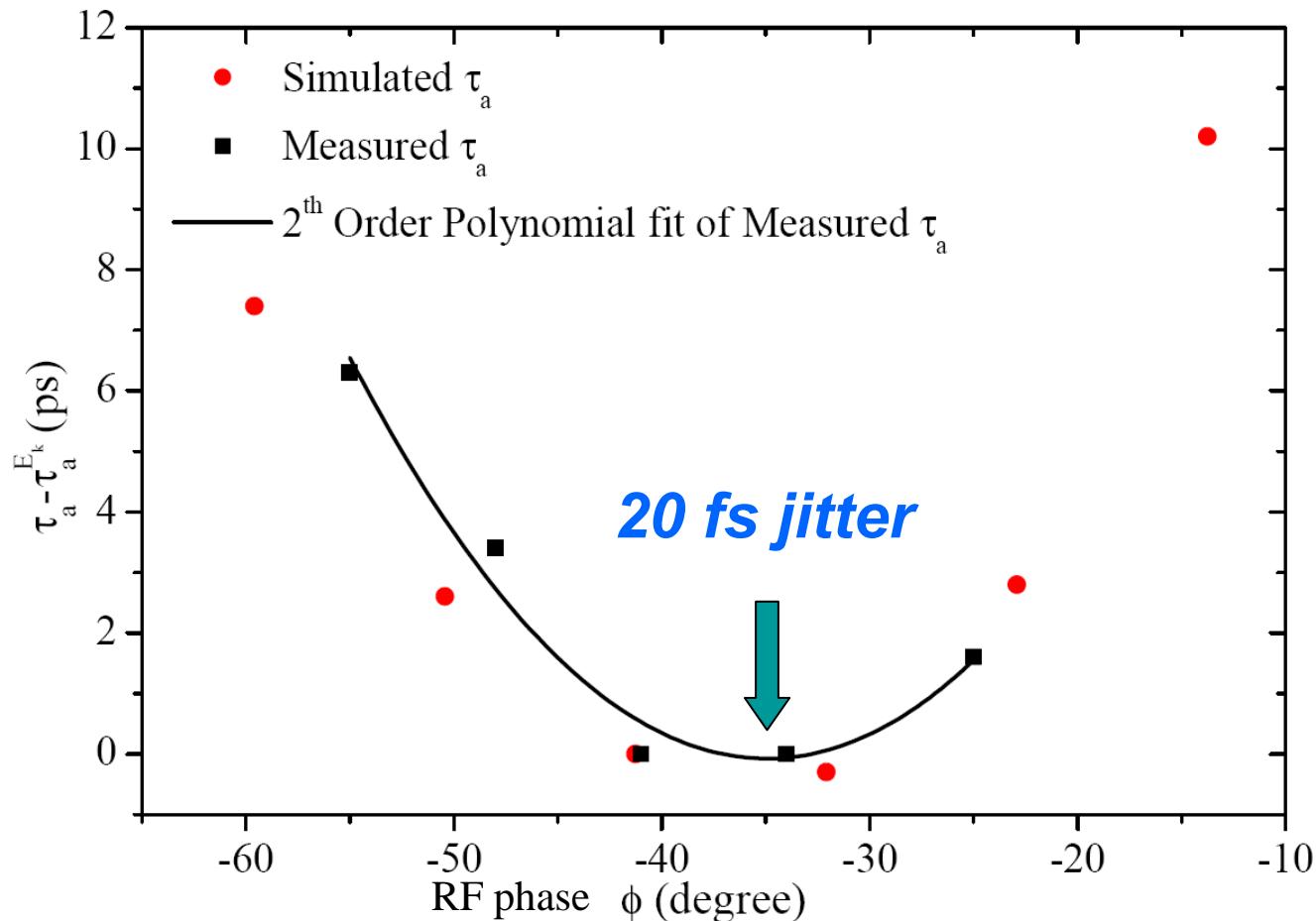
# Bunch length measurement:

Coherent Transition Radiation (CTR)



# Arrival time jitter:

## Coherent Transition Radiation (CTR)



# Performance TU/e gun:

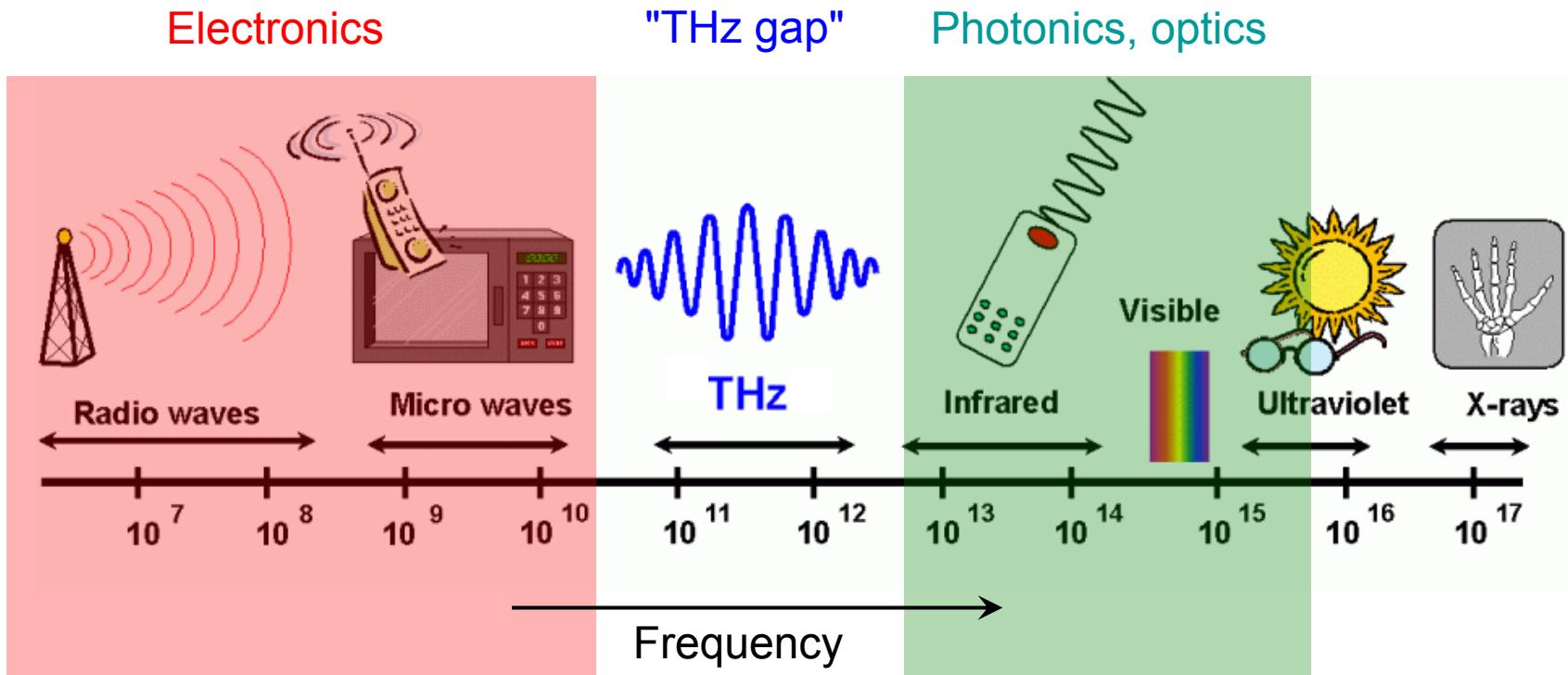
- charge  $Q = 70 \text{ pC}$ ;
  - measured bunch length  $\tau < 2 \text{ ps}$ ;
  - at gun exit  $\tau < 0.5 \text{ ps}$  (GPT);
  - arrival time jitter  $< 20 \text{ fs}$ ;
  - normalized emittance  $\varepsilon_n = 1 \text{ mm}\cdot\text{mrad}$ .
- peak current 35-140 A*

## LCLS injector (Akre et al., PRSTAB 11, 030703, 2008)

- normalized emittance:  $\varepsilon_n = 1 \text{ mm}\cdot\text{mrad}$
- peak current:  $100 \text{ A}$  ( $1 \text{ nC} / 10 \text{ ps}$ )

## Part II: THz generation

# THz radiation



# THz radiation

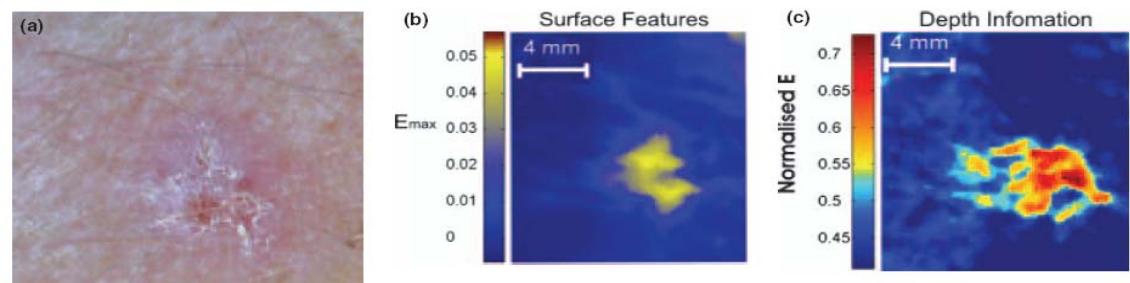


Many materials transparent: “*T*-rays”

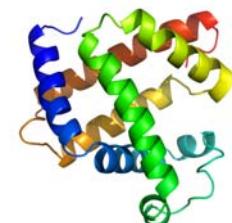


Security: *body scan*

Medical applications: *skin cancer diagnostics*

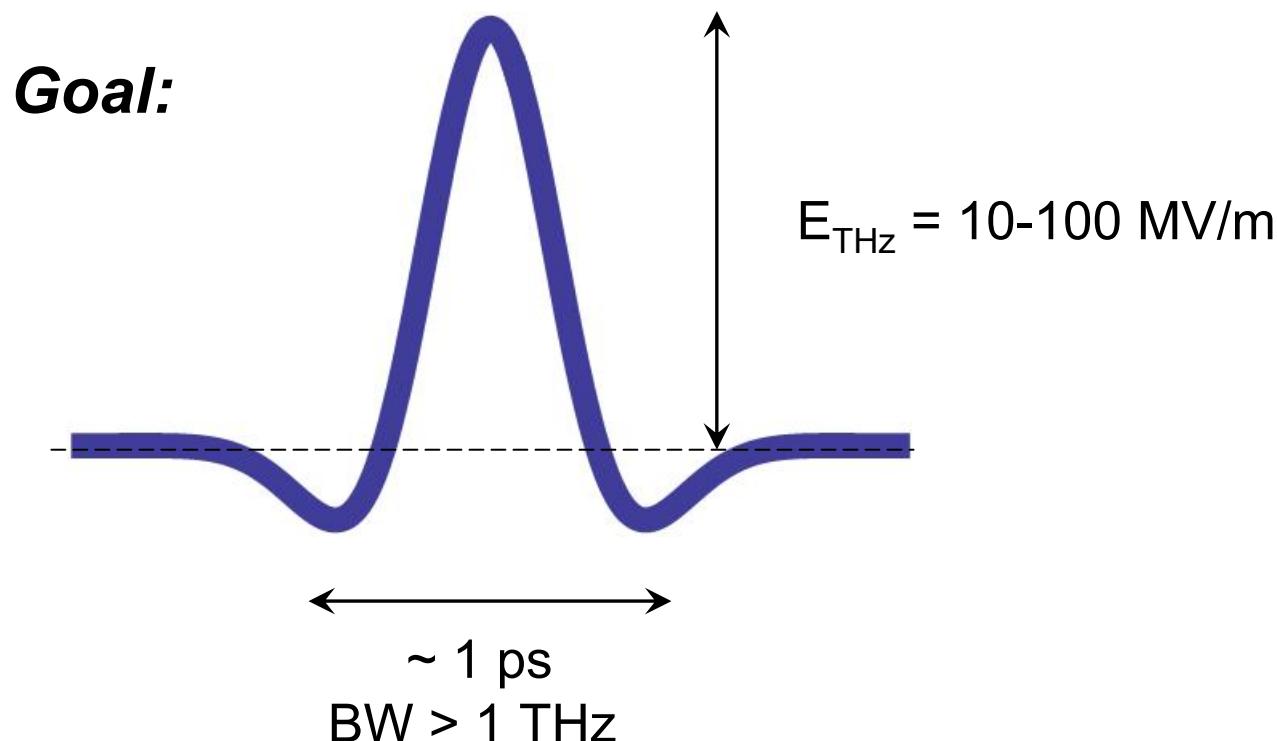


Science: *charge carriers dynamics, molecular physics, imaging of biological tissues, ...*



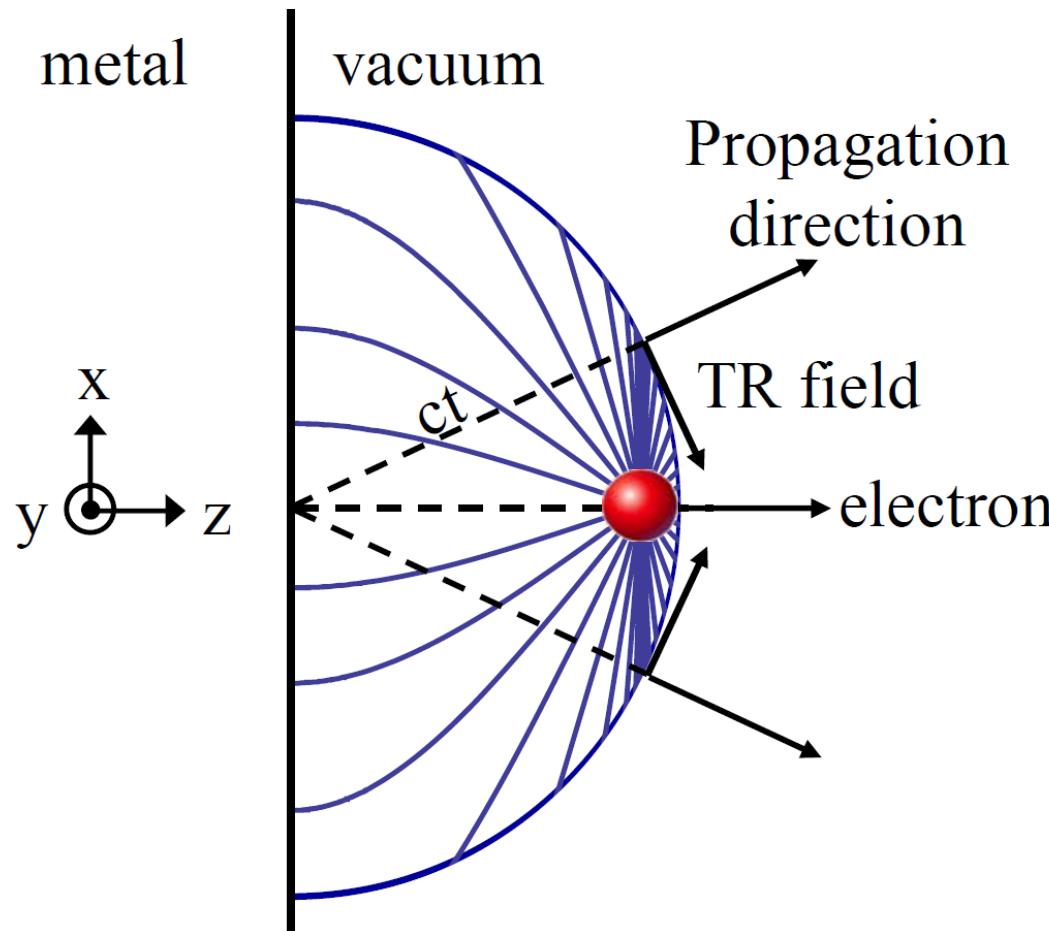
# Single-cycle THz pulses

generated by Coherent Transition Radiation (CTR)



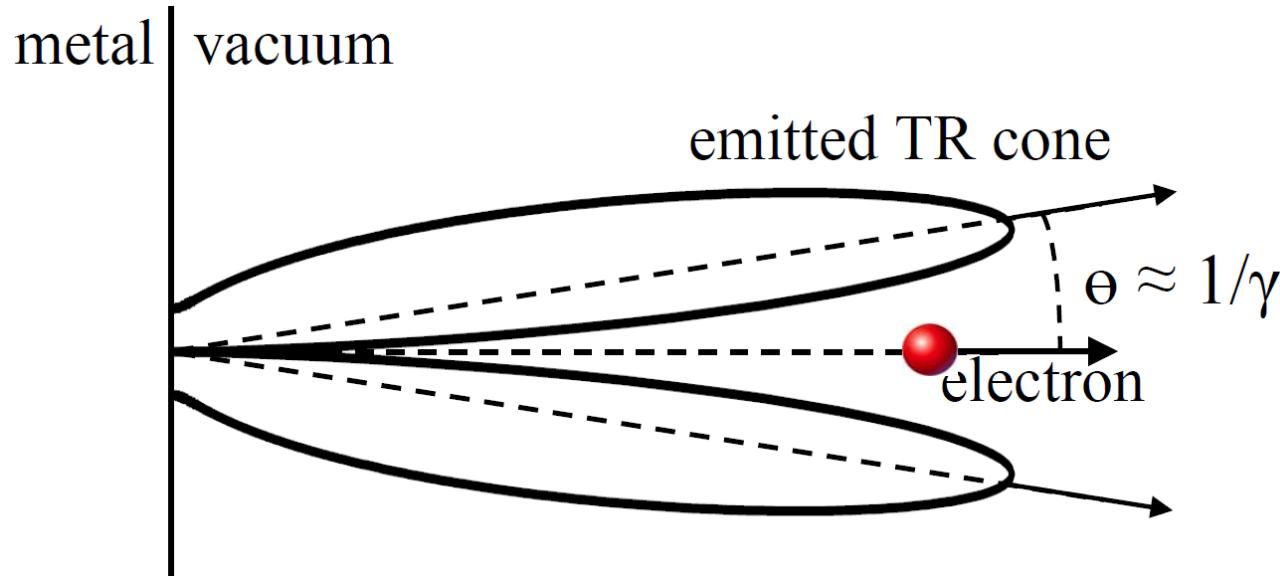
# Single-cycle THz pulses

generated by Coherent Transition Radiation (CTR)



# Single-cycle THz pulses

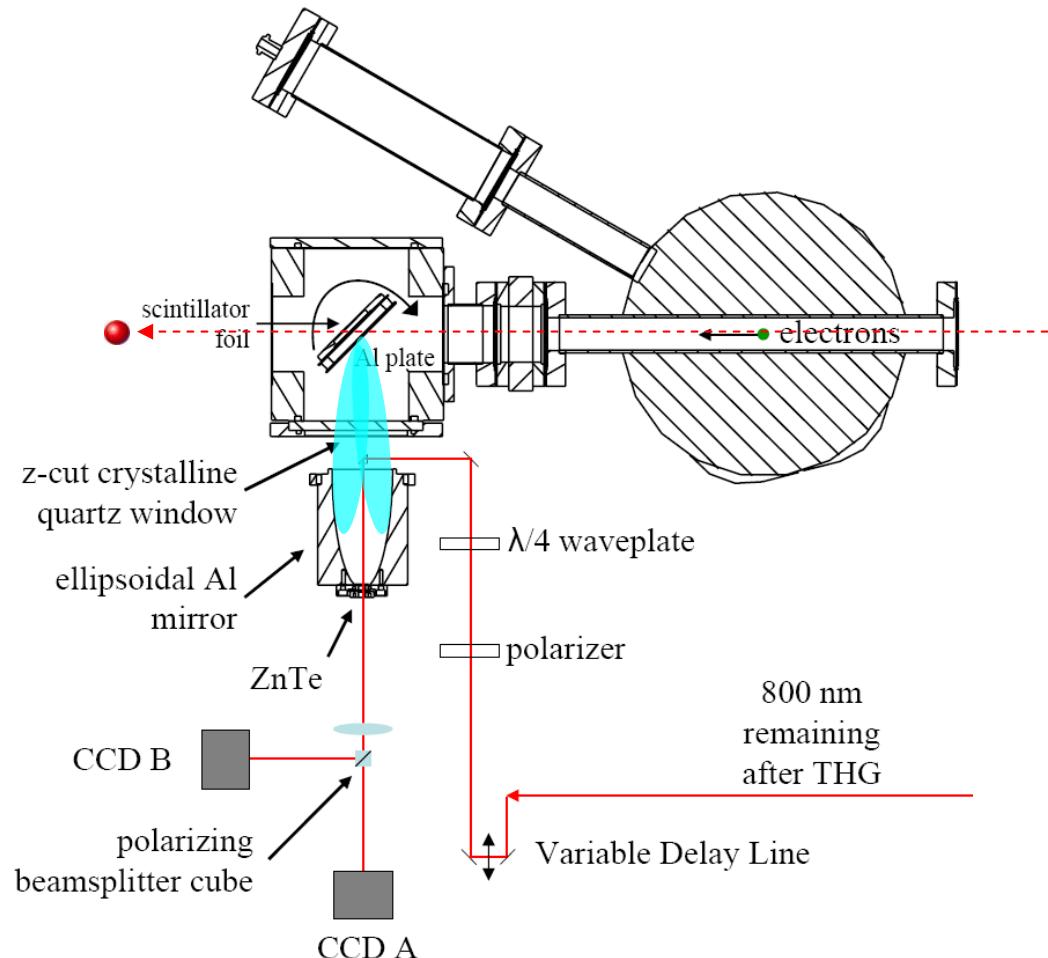
generated by Coherent Transition Radiation (CTR)



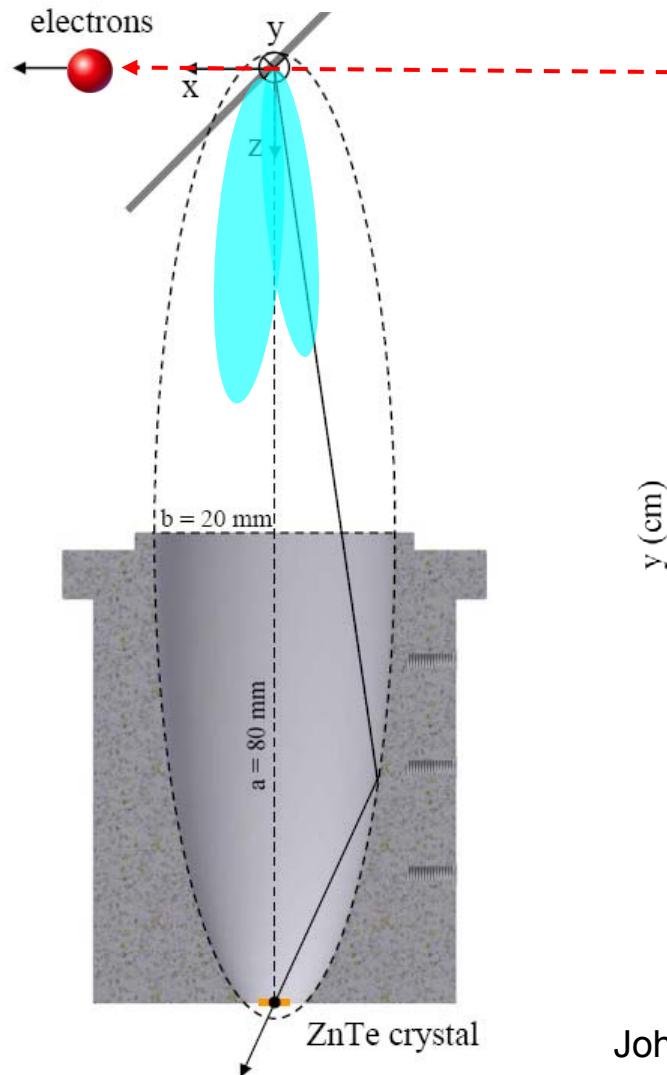
- $\sim 0.1$  eV per electron
- Coherent addition  $\rightarrow \sim N^2 \rightarrow$  ***many  $\mu$ J per bunch***
- bunch length 1 ps  $\rightarrow > 1$  THz bandwidth

# Single-cycle THz pulses

generated by Coherent Transition Radiation (CTR)

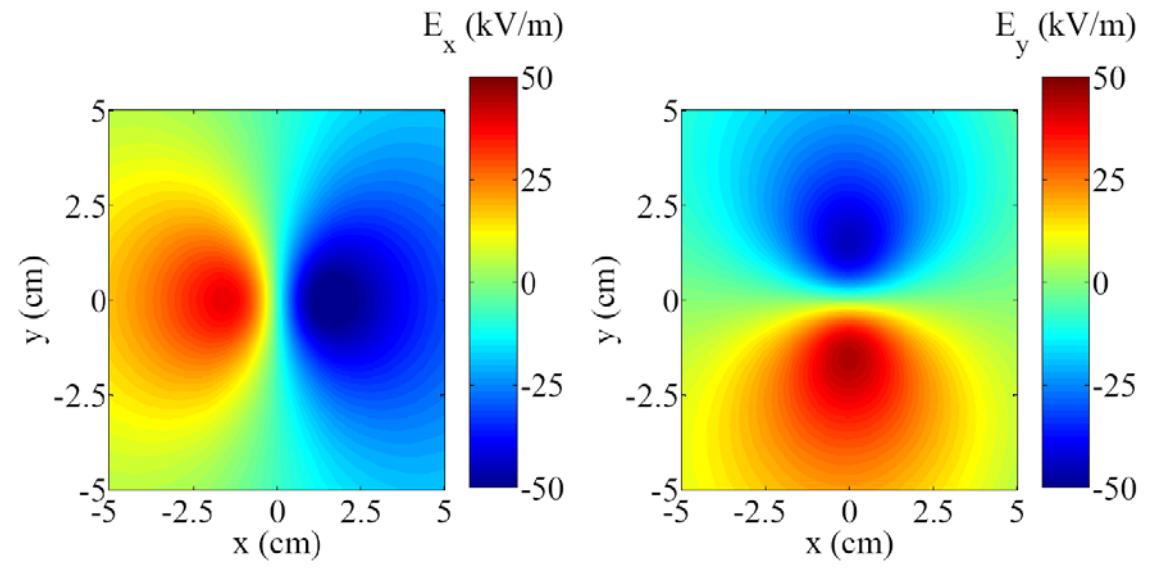


# Single-cycle THz pulses



CTR: *radially polarized*

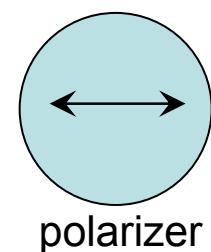
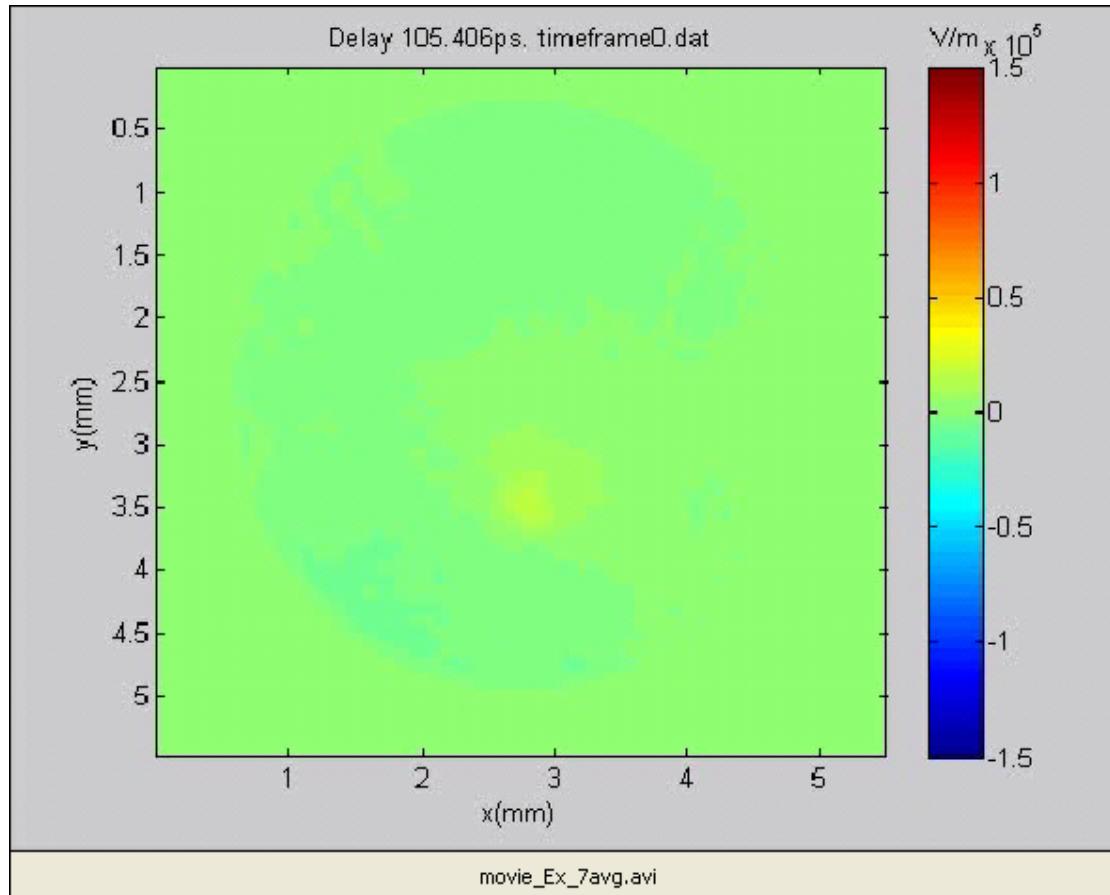
unfocused CTR for  $r = 10 \text{ cm}$  and  $t = r/c$



*Expected signal*

# Single-cycle THz pulses

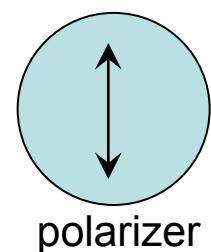
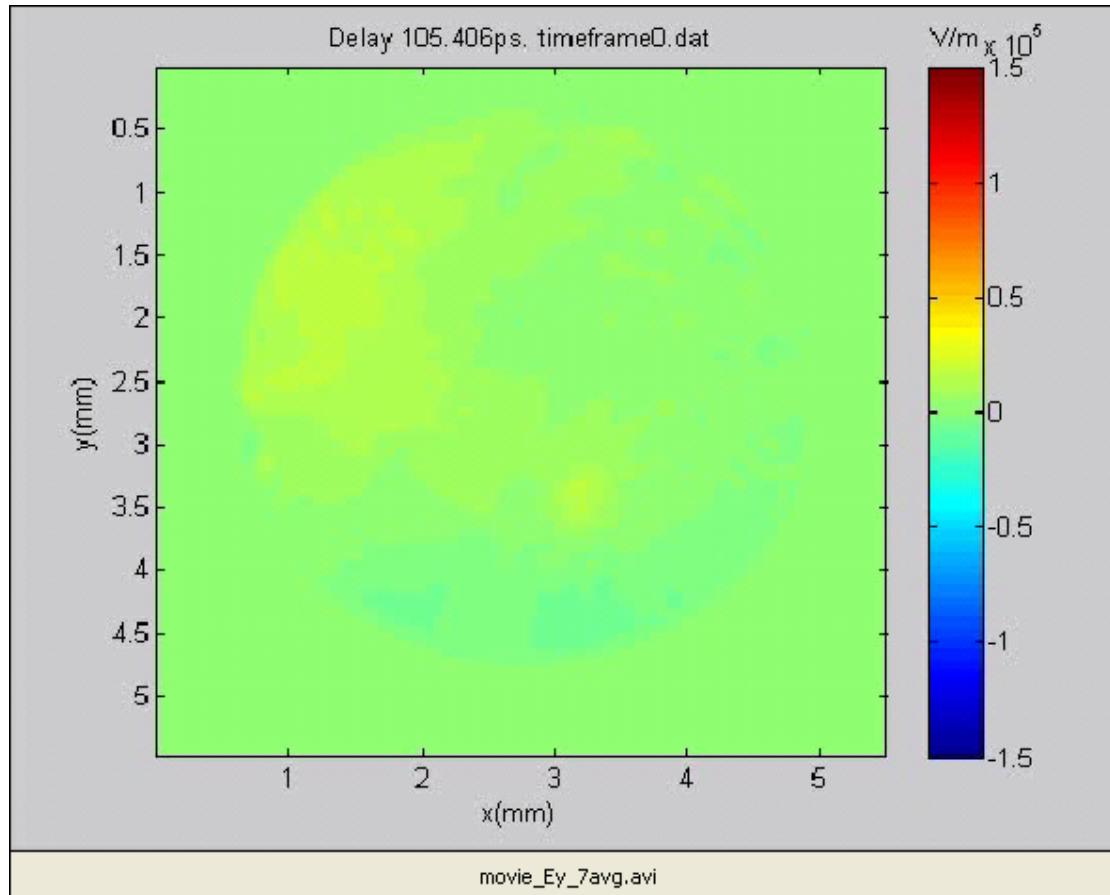
generated by Coherent Transition Radiation (CTR)



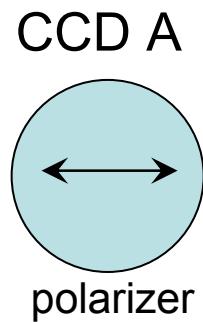
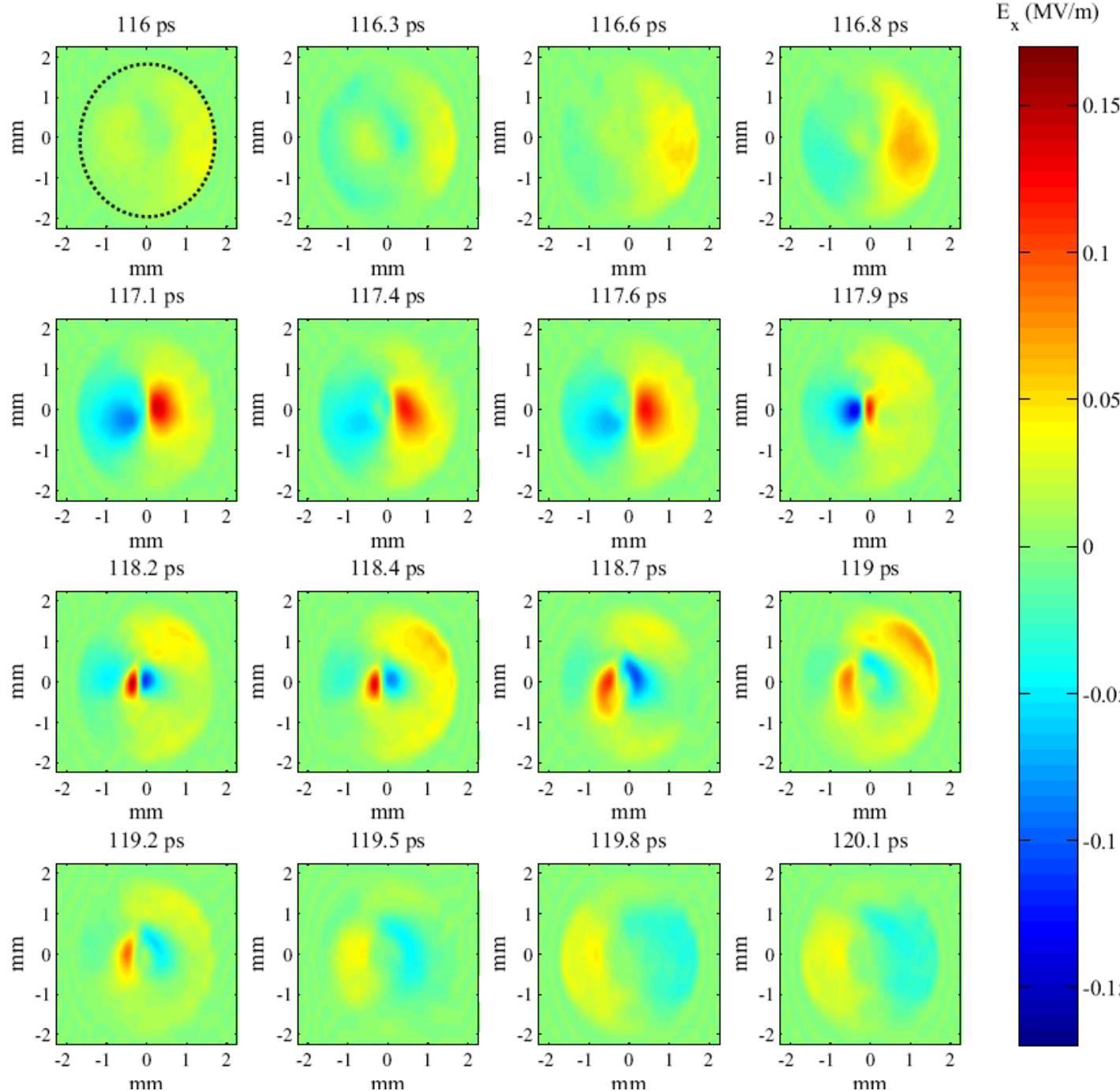
CCD A

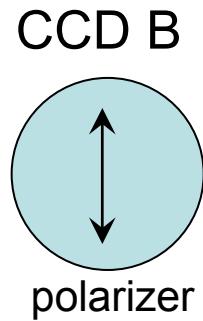
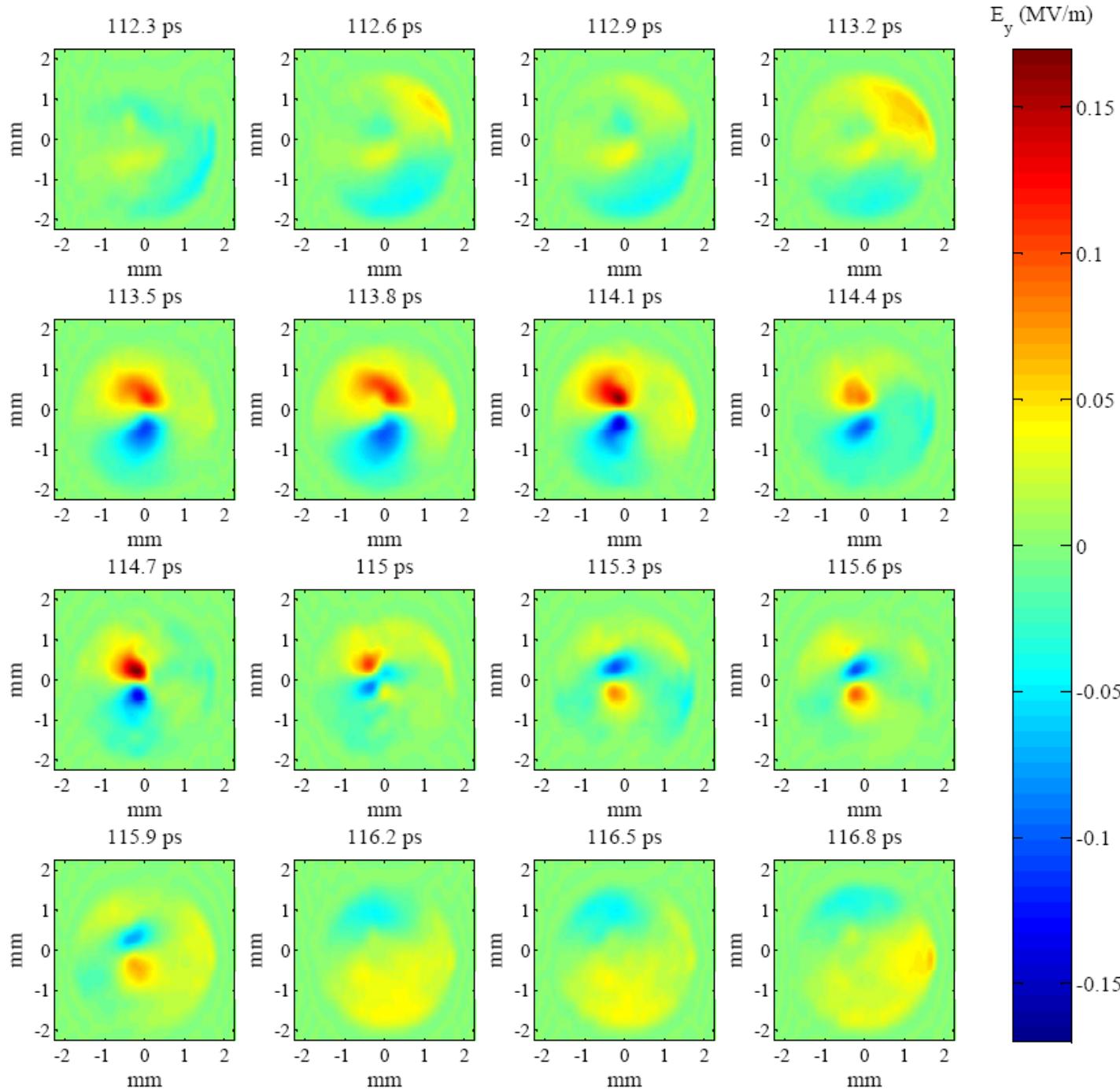
# Single-cycle THz pulses

generated by Coherent Transition Radiation (CTR)



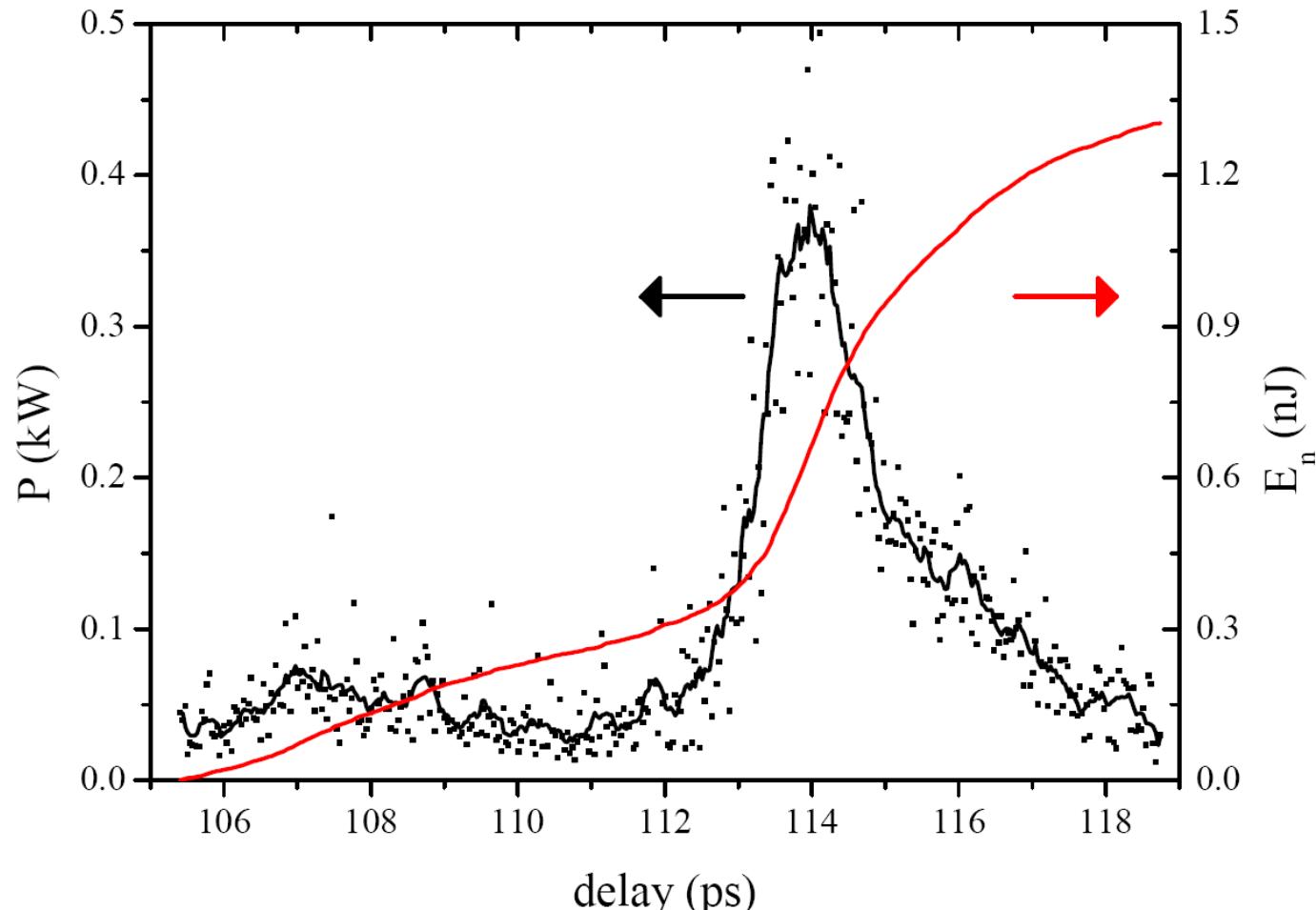
CCD B





# Single-cycle THz pulses

THz power & energy in focus



# Single-cycle THz pulses

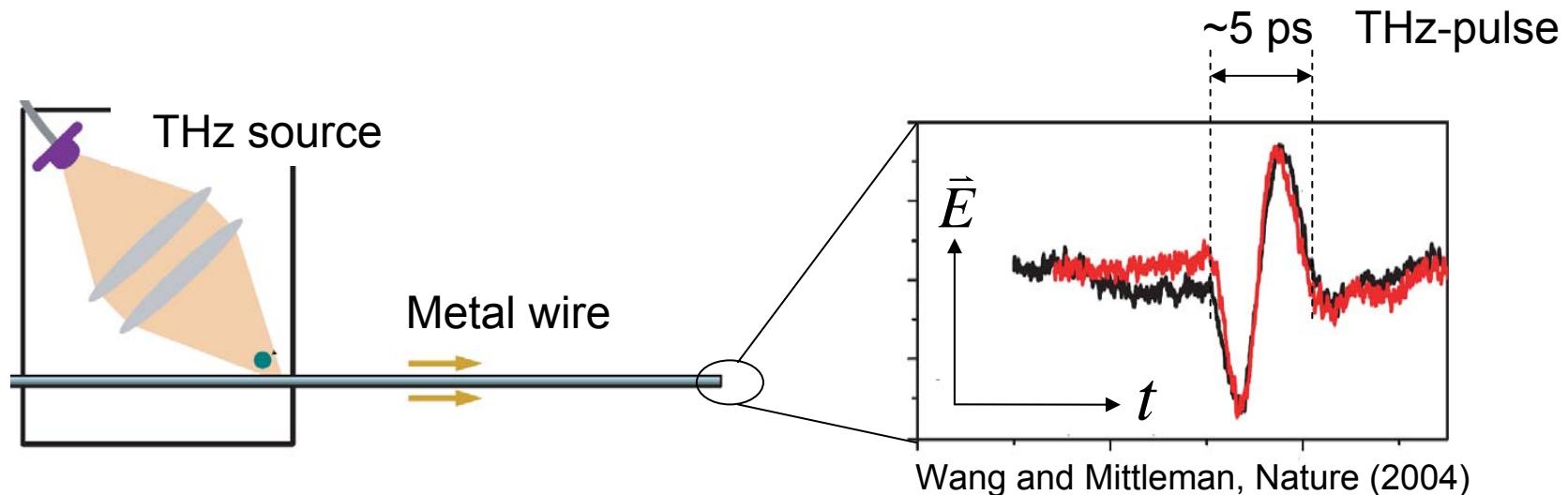
generated by Coherent Transition Radiation (CTR)

- *Field distribution in focus well understood;*
- *10-100× more energy in focus by shorter bunches and improved collection efficiency;*
- *~ $\mu$ J per pulse in focus **not possible** with RF photogun;*
- *fundamental problem: **diffraction-limited focusing of single-cycle pulses!***

# THz surface plasmons

THz guiding on a wire

*Evanescence EM surface waves = ‘Surface Plasmon Polaritons (SPPs)’*

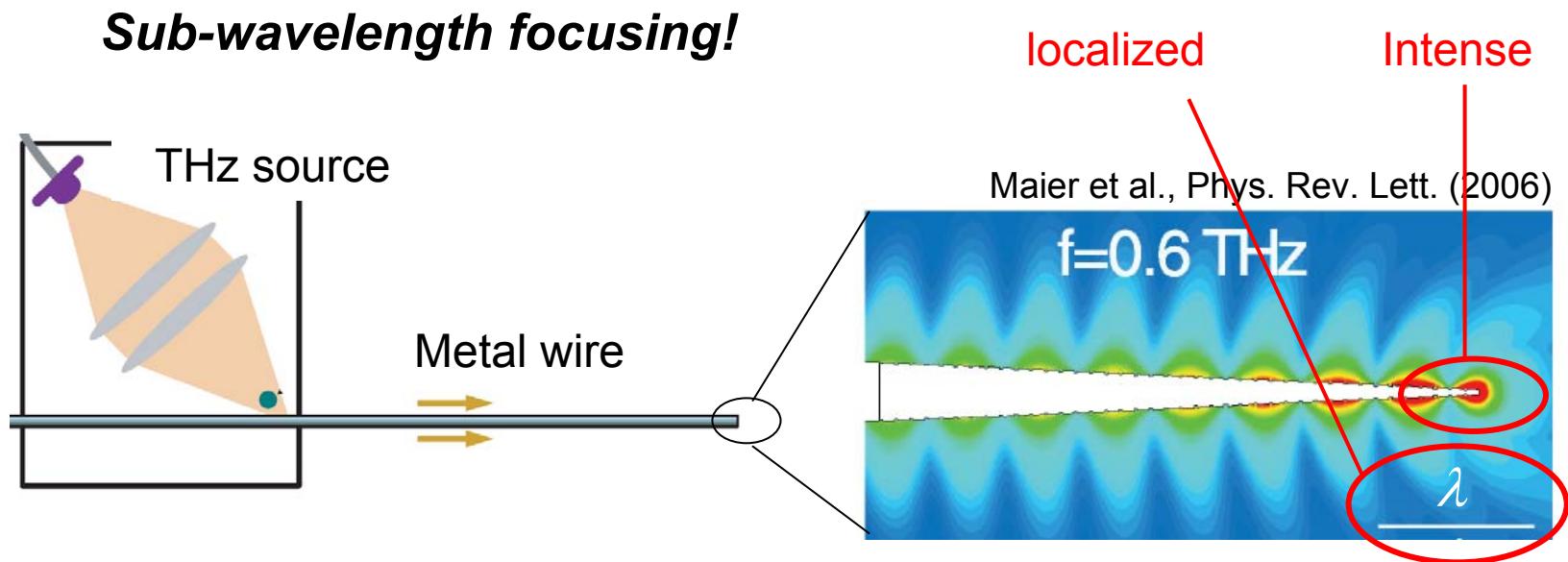


*Metal wire is a promising waveguide*

‘THz endoscope’

# THz surface plasmons

THz guiding on a wire

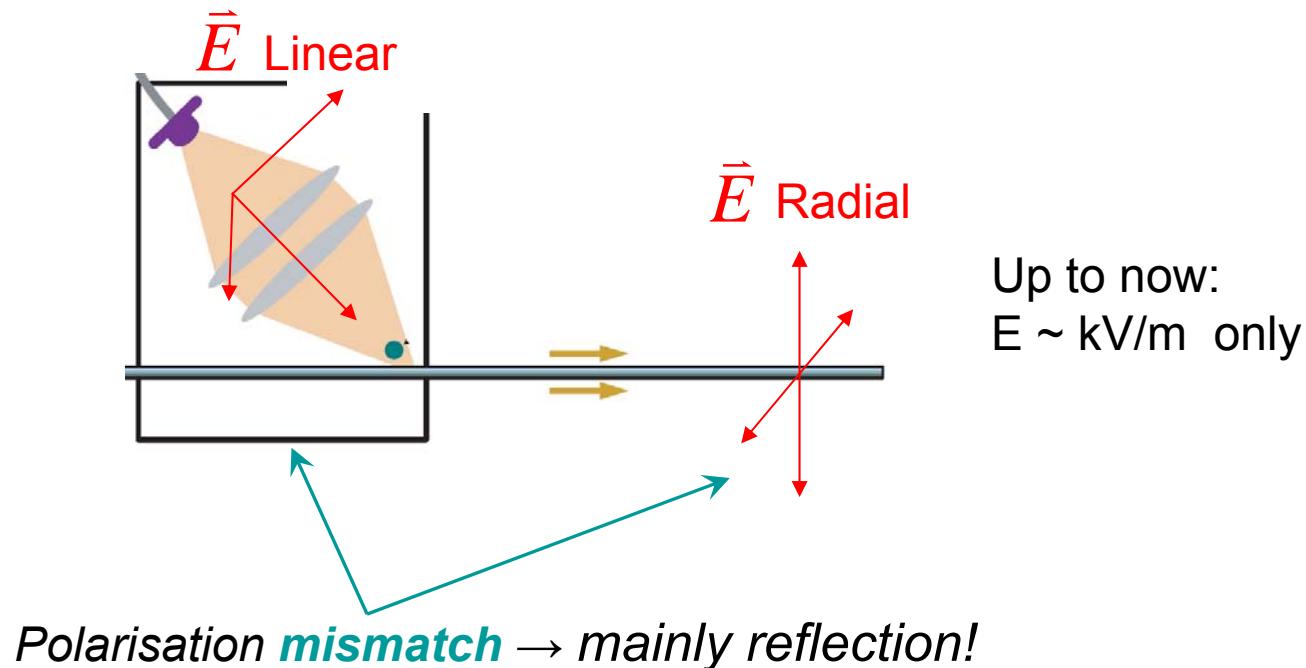


→ New THz research: *Single molecule detection, non-linear optics, etc.*

# THz surface plasmons

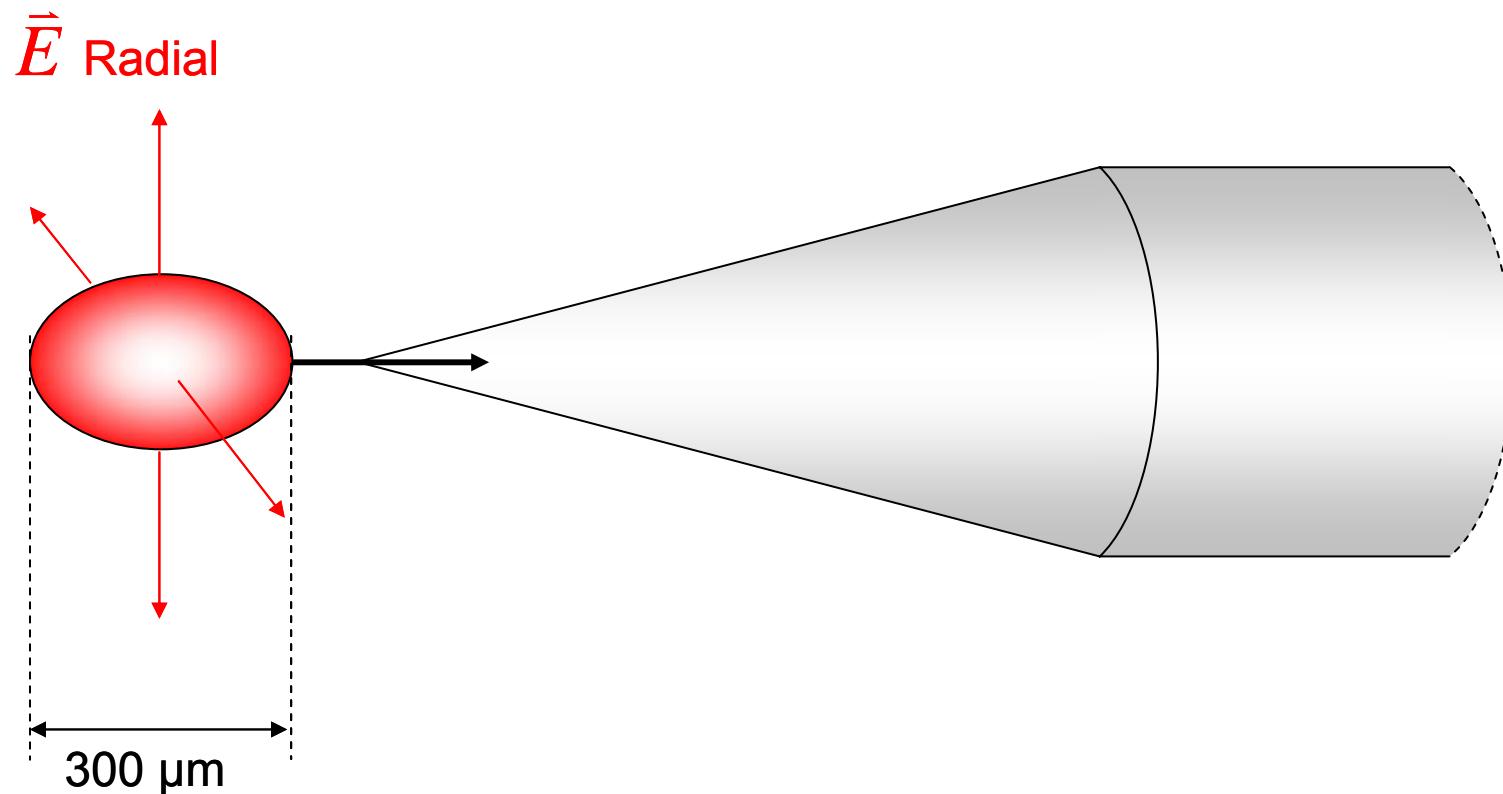
THz guiding on a wire

Problem: *generation of THz surface plasmons!*



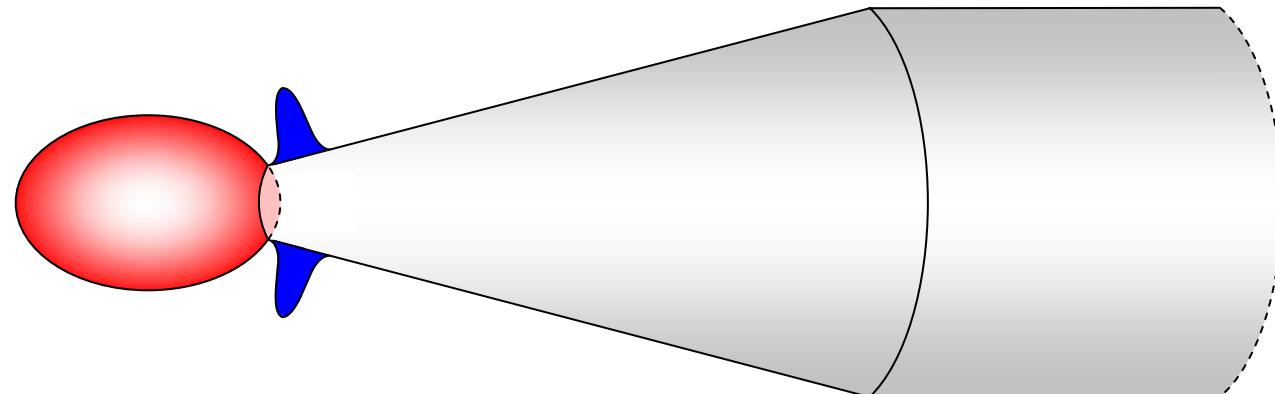
# THz surface plasmons

Idea: *shoot relativistic bunches into wire tip*



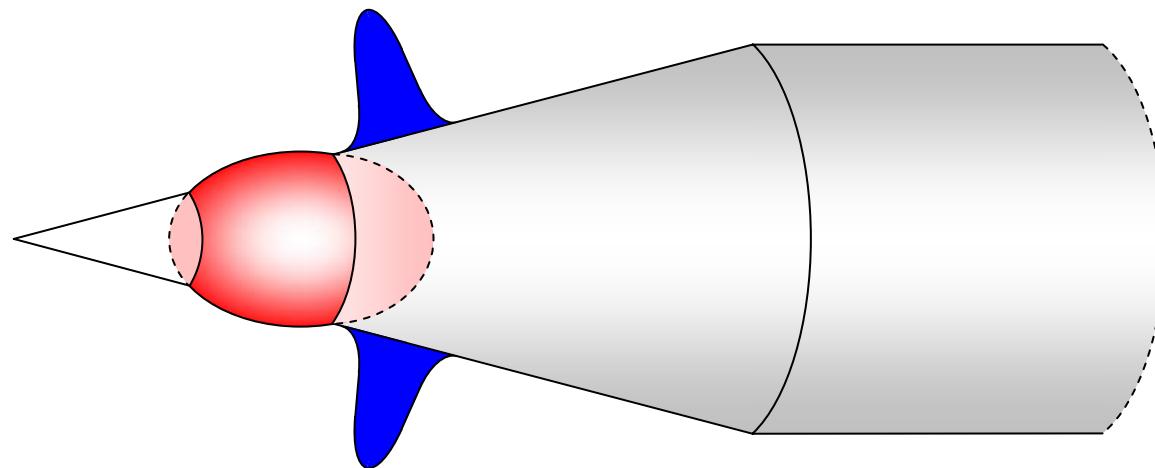
# THz surface plasmons

Idea: *shoot relativistic bunches into wire tip*



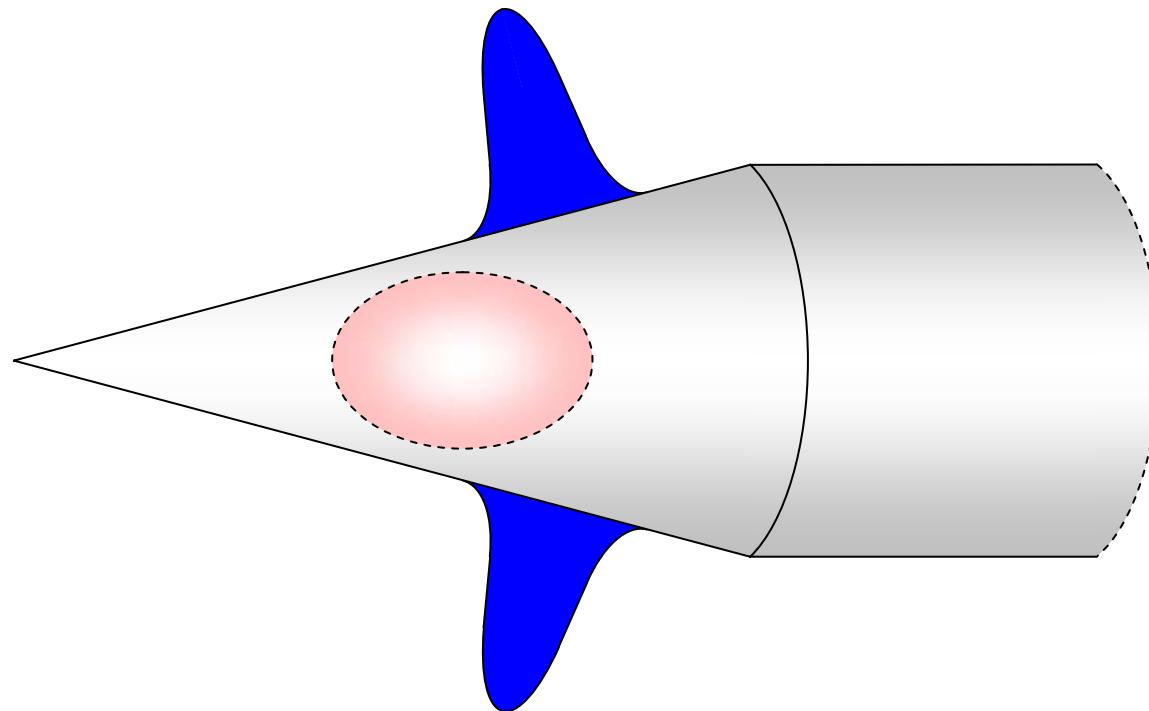
# THz surface plasmons

Idea: *shoot relativistic bunches into wire tip*



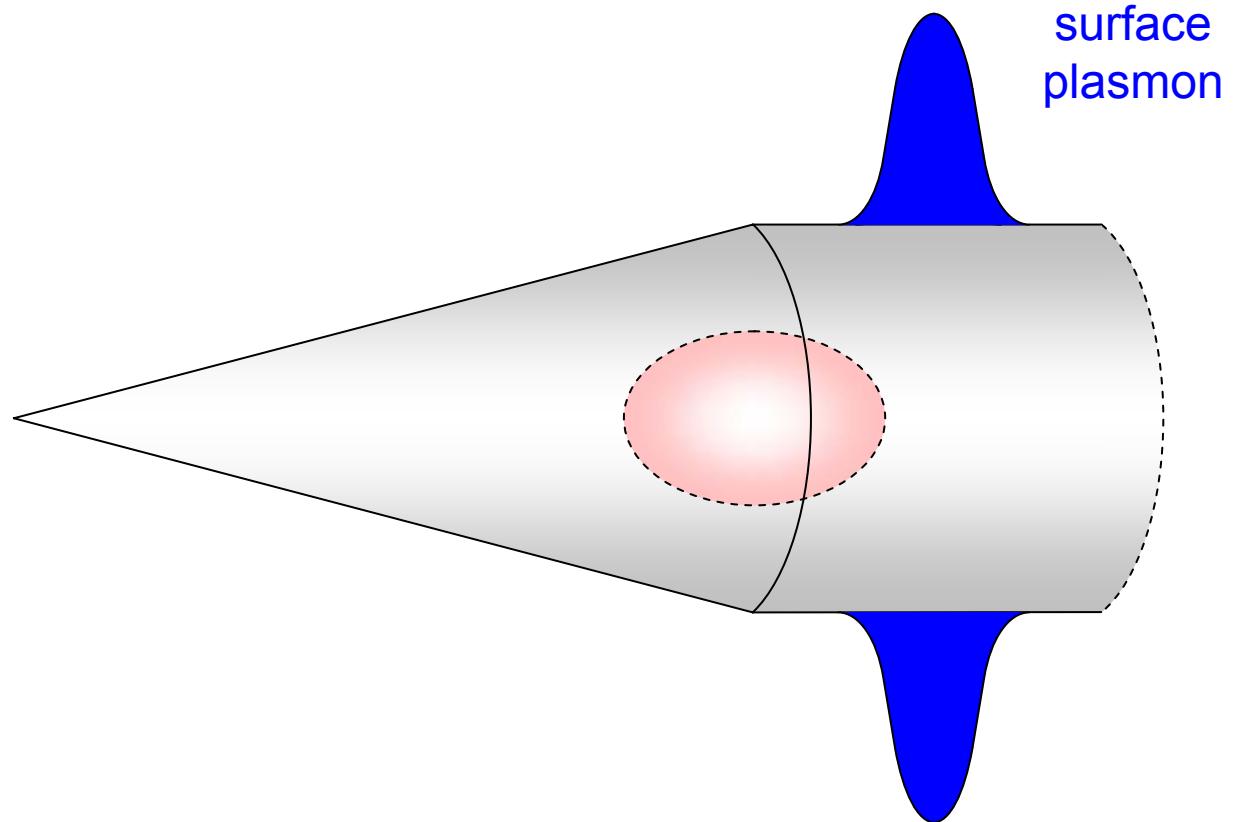
# THz surface plasmons

Idea: *shoot relativistic bunches into wire tip*



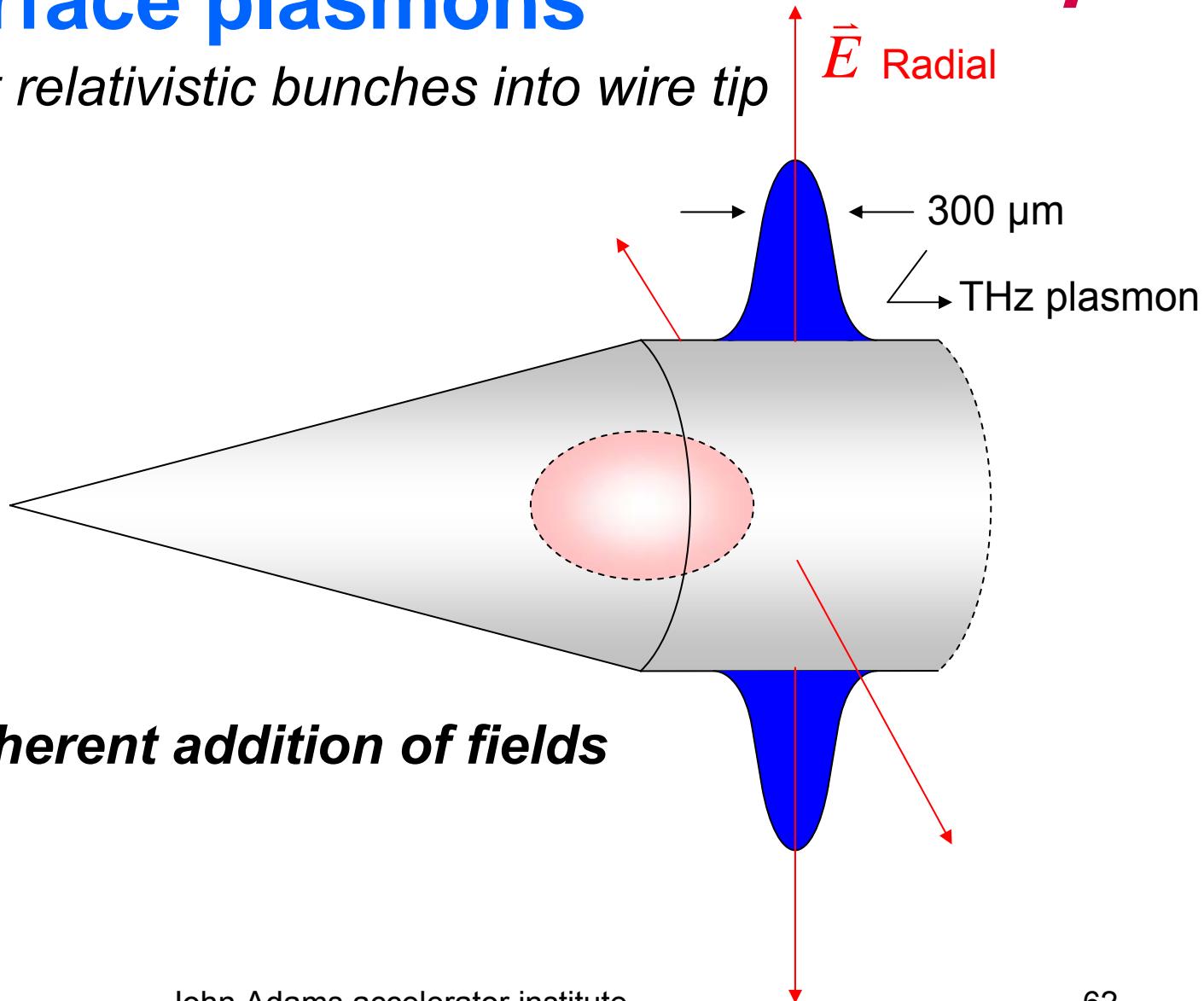
# THz surface plasmons

Idea: *shoot relativistic bunches into wire tip*



# THz surface plasmons

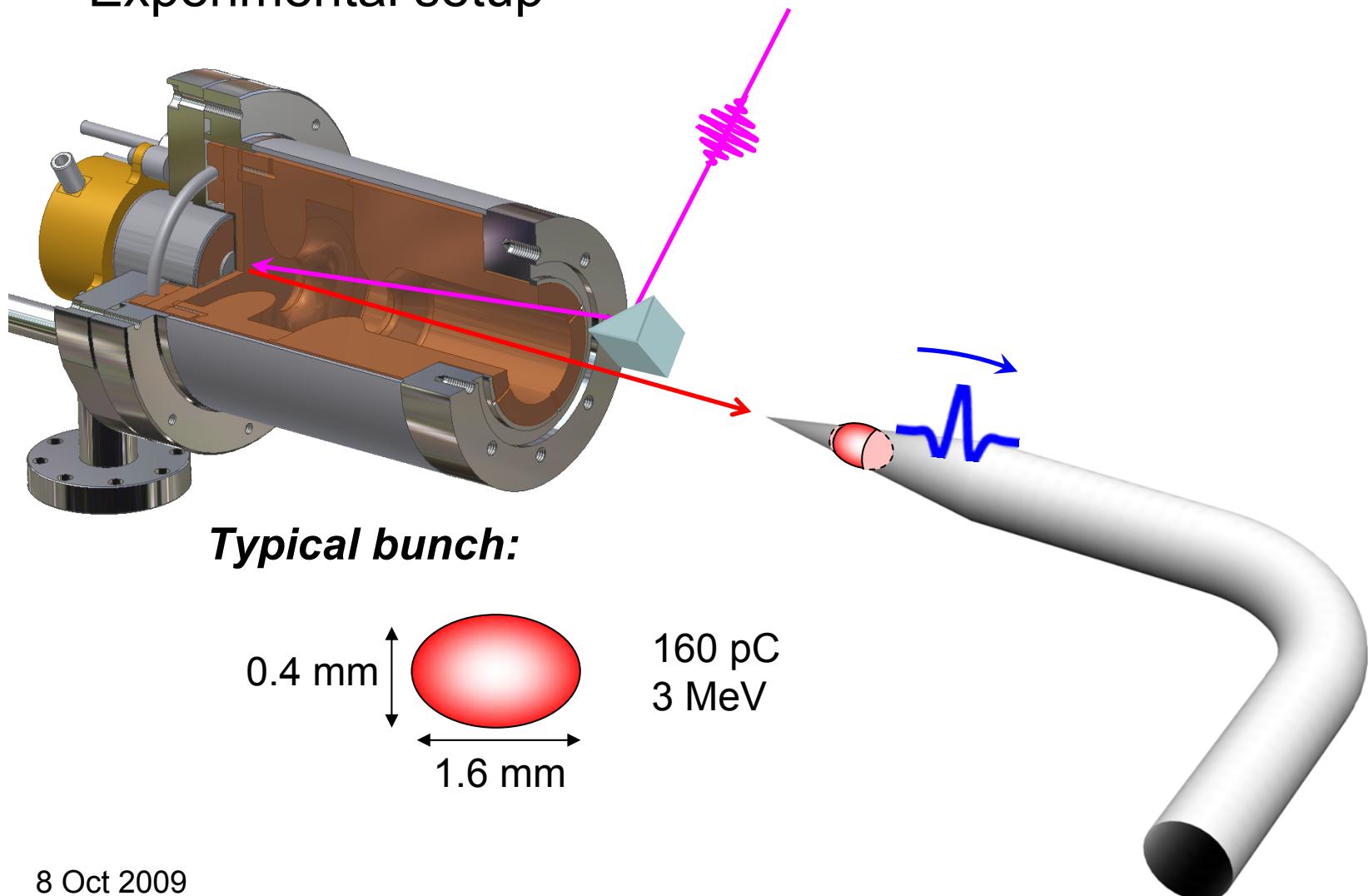
Idea: *shoot relativistic bunches into wire tip*



Again: **coherent addition of fields**

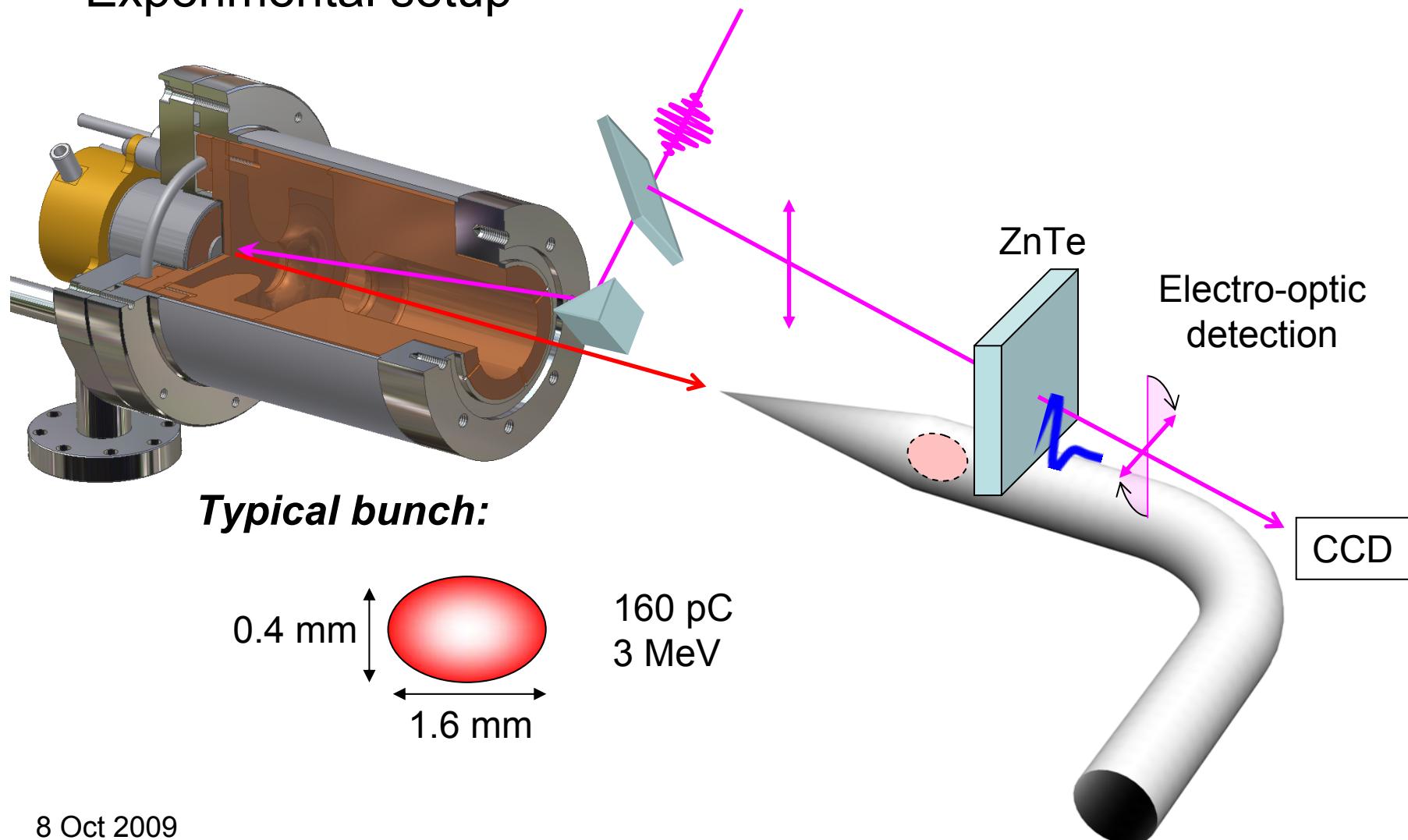
# THz surface plasmons

## Experimental setup



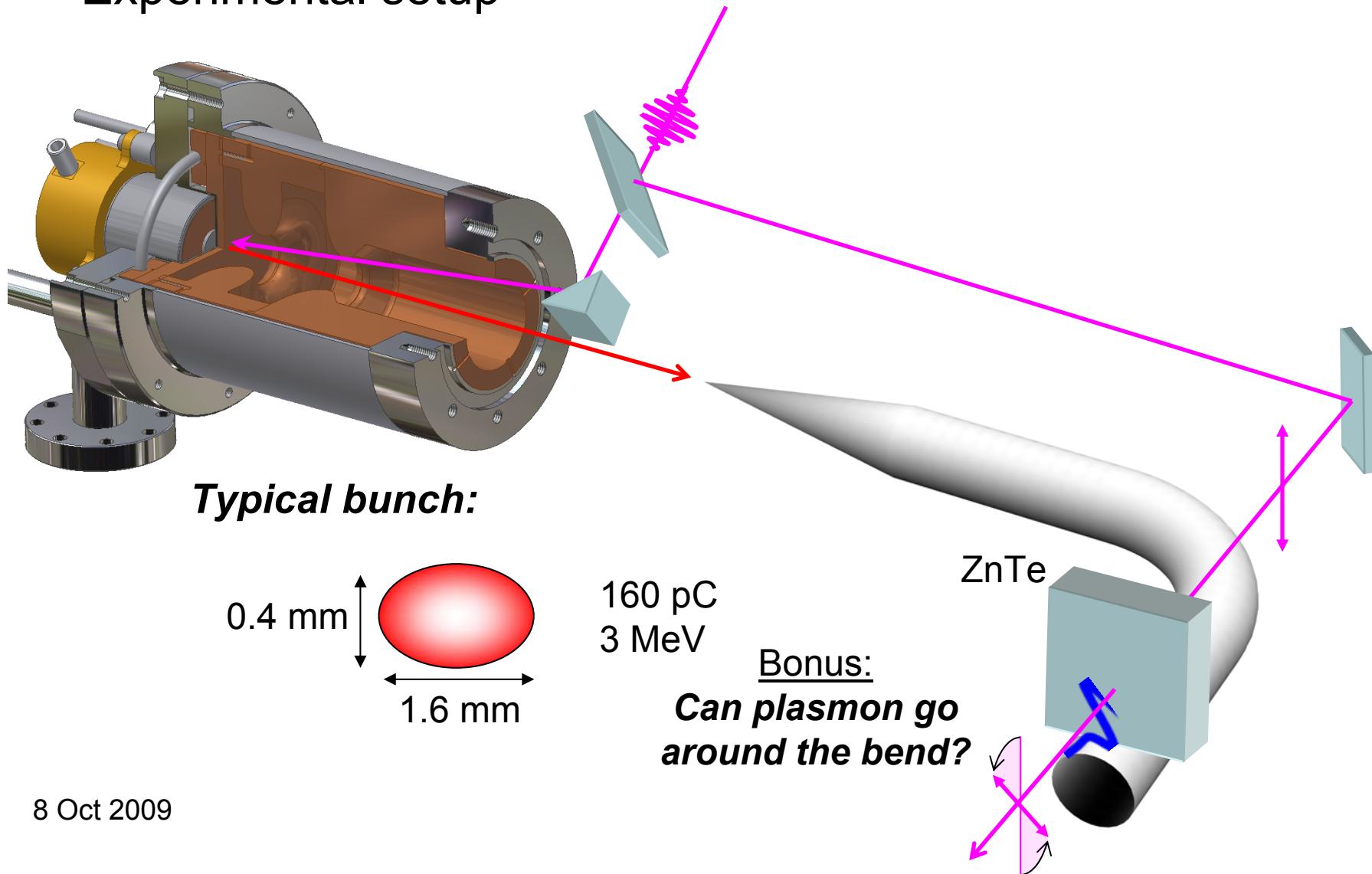
# THz surface plasmons

## Experimental setup



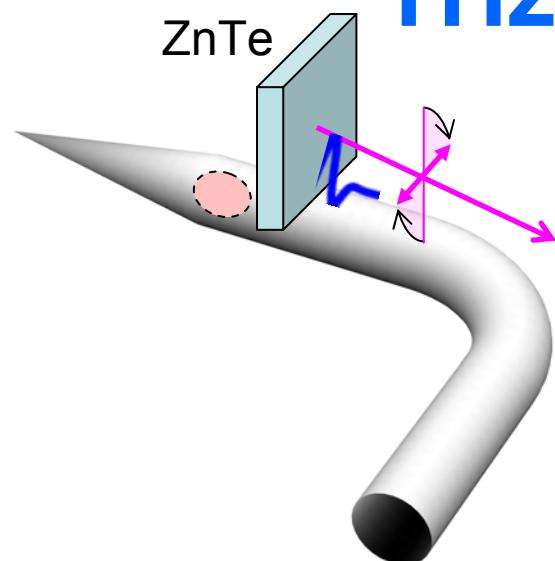
# THz surface plasmons

## Experimental setup



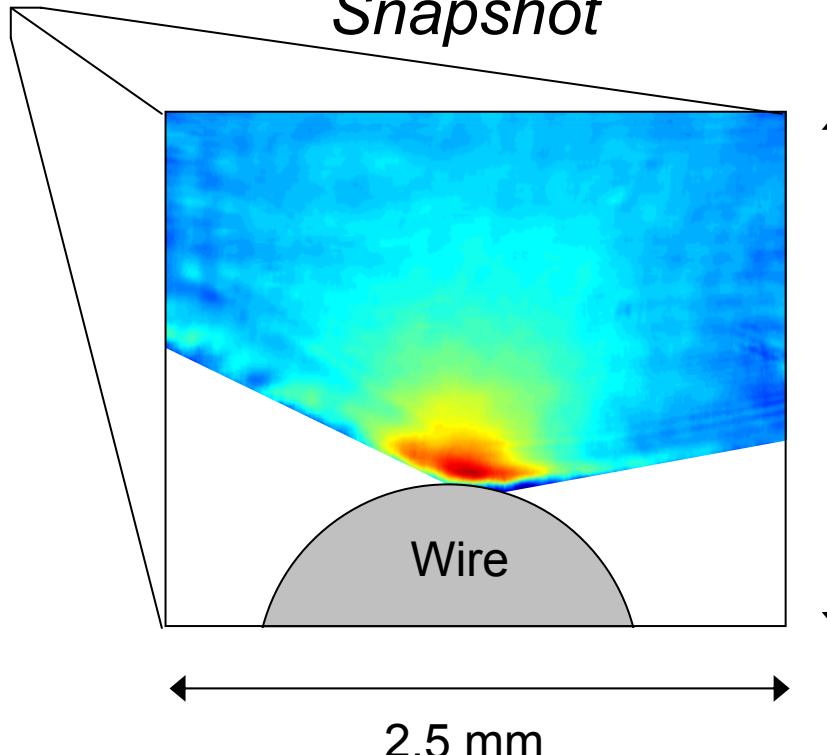
# THz surface plasmons

TU/e

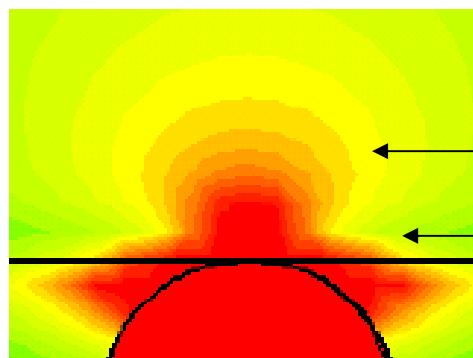


Measured electric field

Snapshot



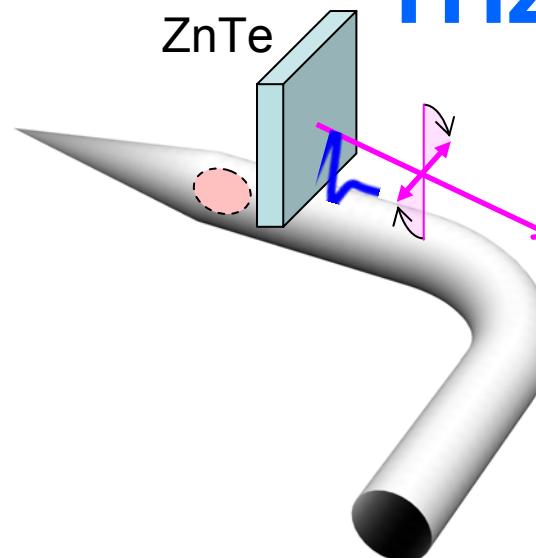
Simulated:  
Plasmon dispersed  
by ZnTe



John Adams accelerator institute

# THz surface plasmons

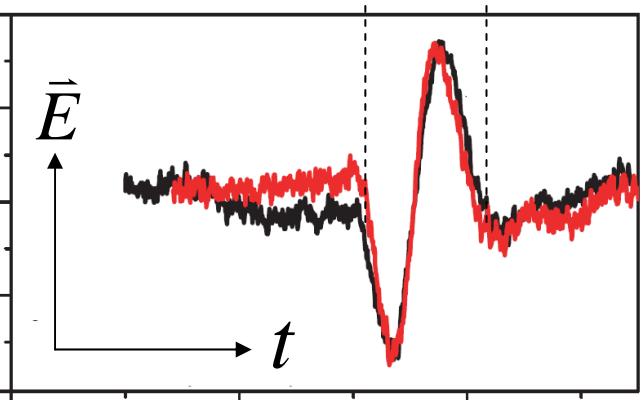
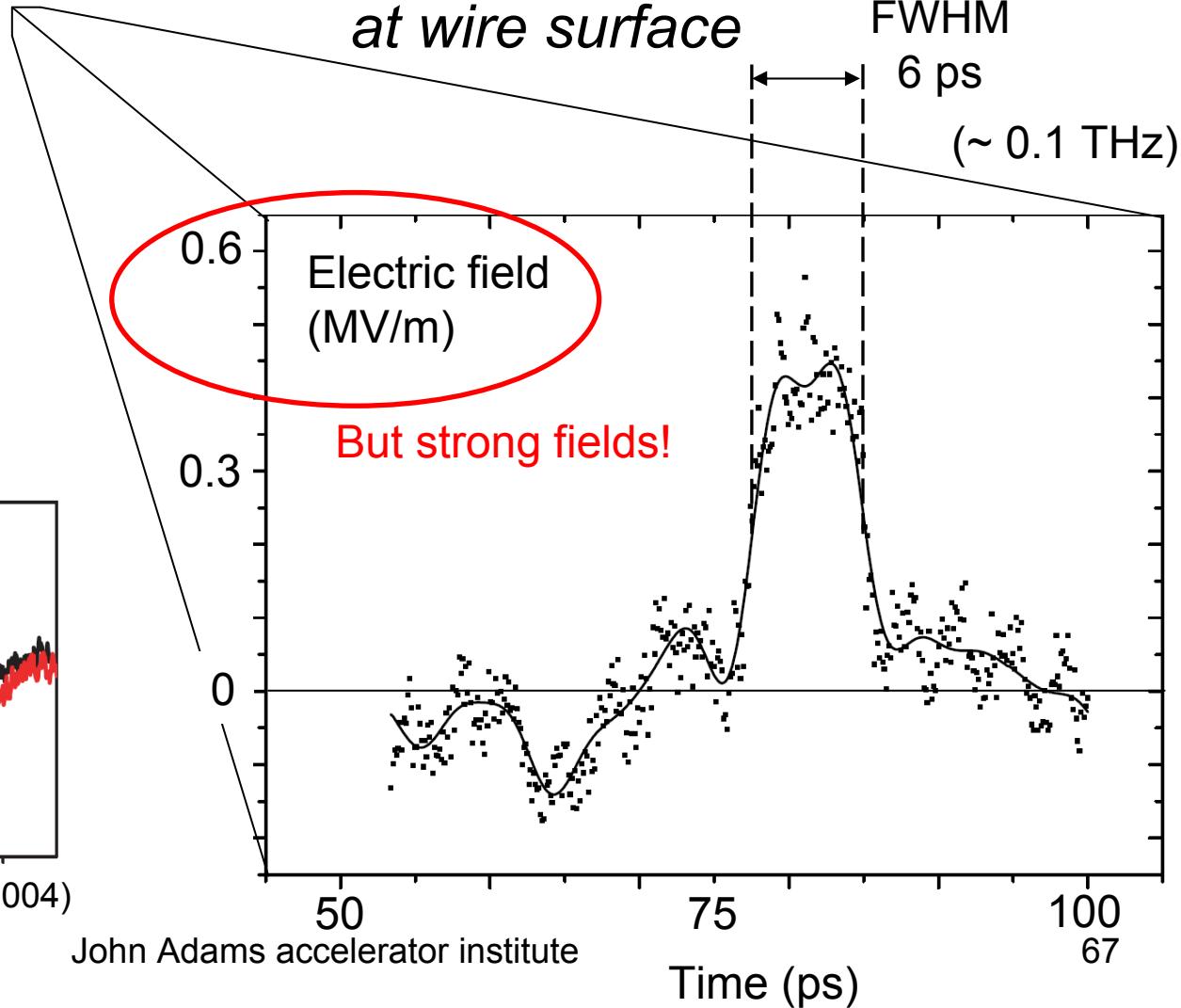
TU/e



Measured electric field

*Field in vacuum  
at wire surface*

FWHM  
6 ps  
(~ 0.1 THz)



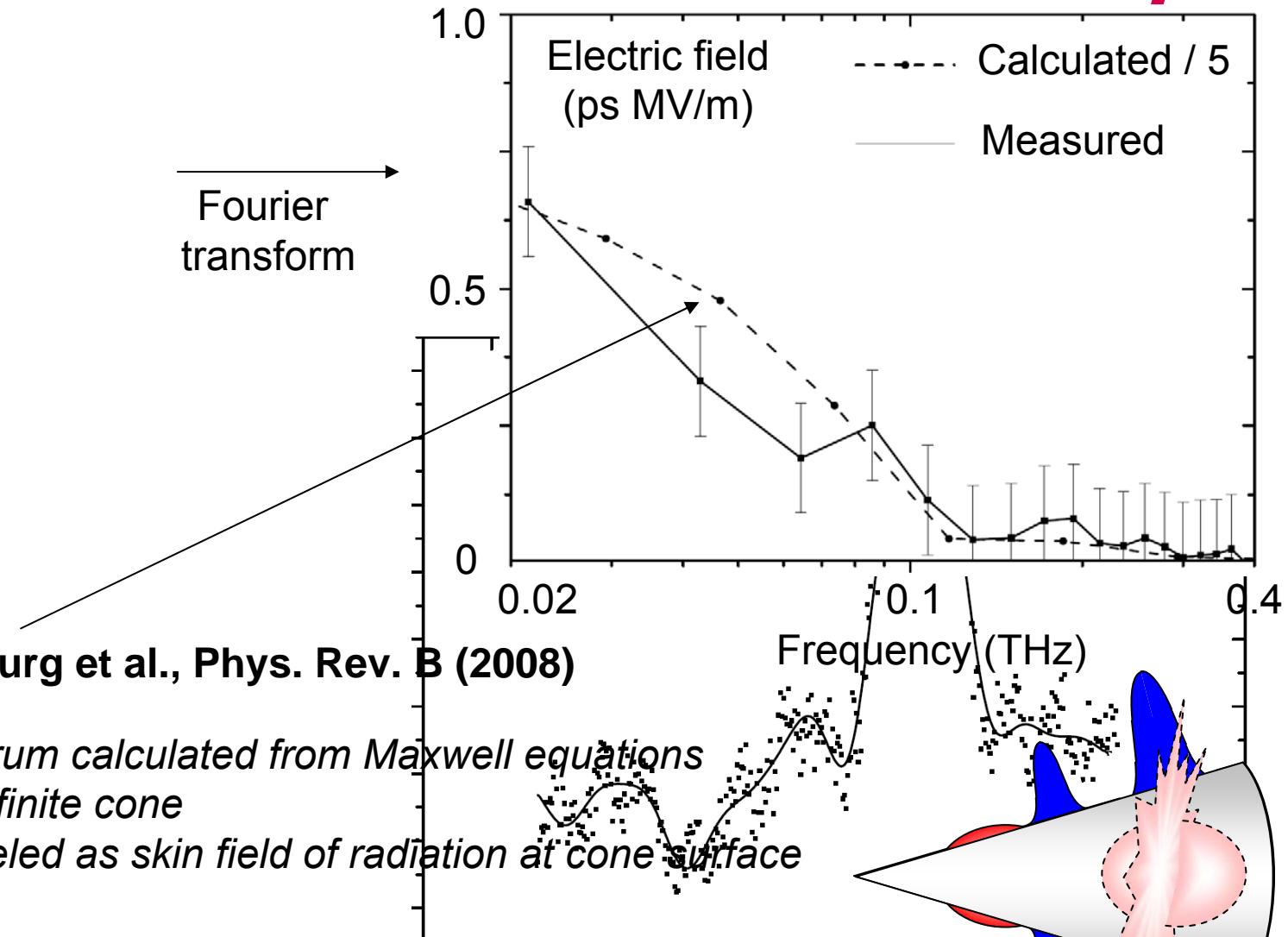
Wang and Mittleman, Nature (2004)

8 Oct 2009

John Adams accelerator institute

67

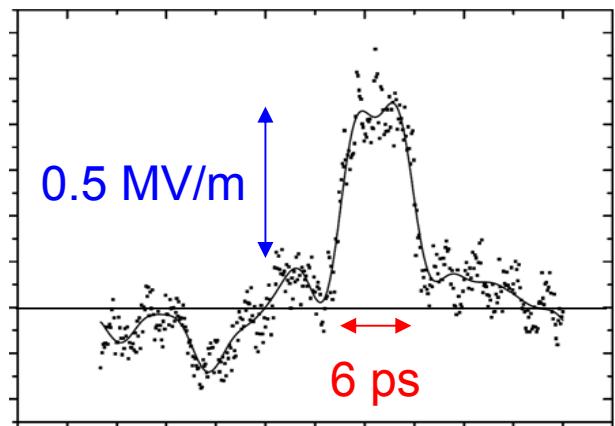
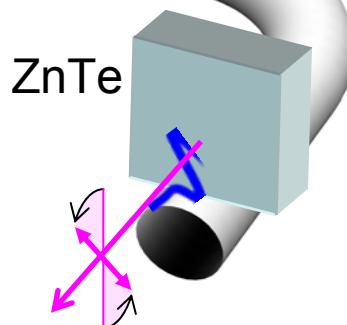
# THz surface plasmons



# THz surface plasmons

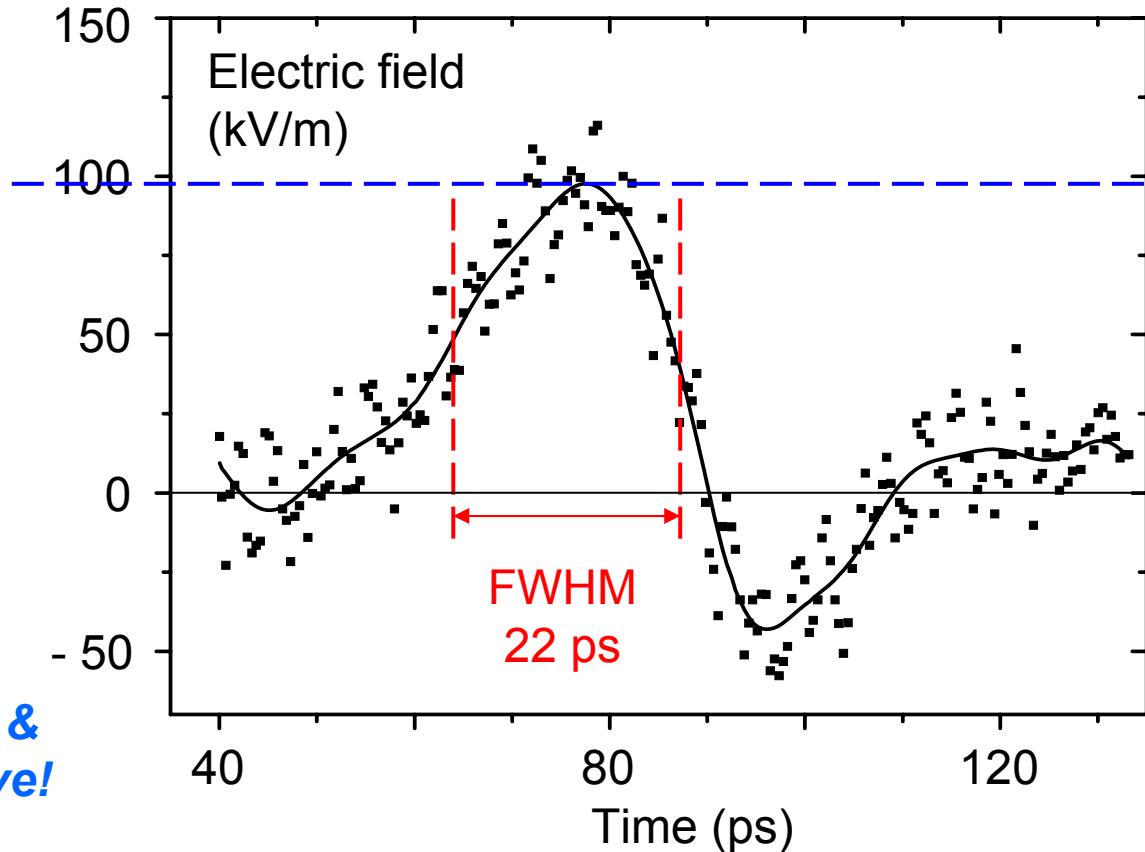
TU/e

After the bend?



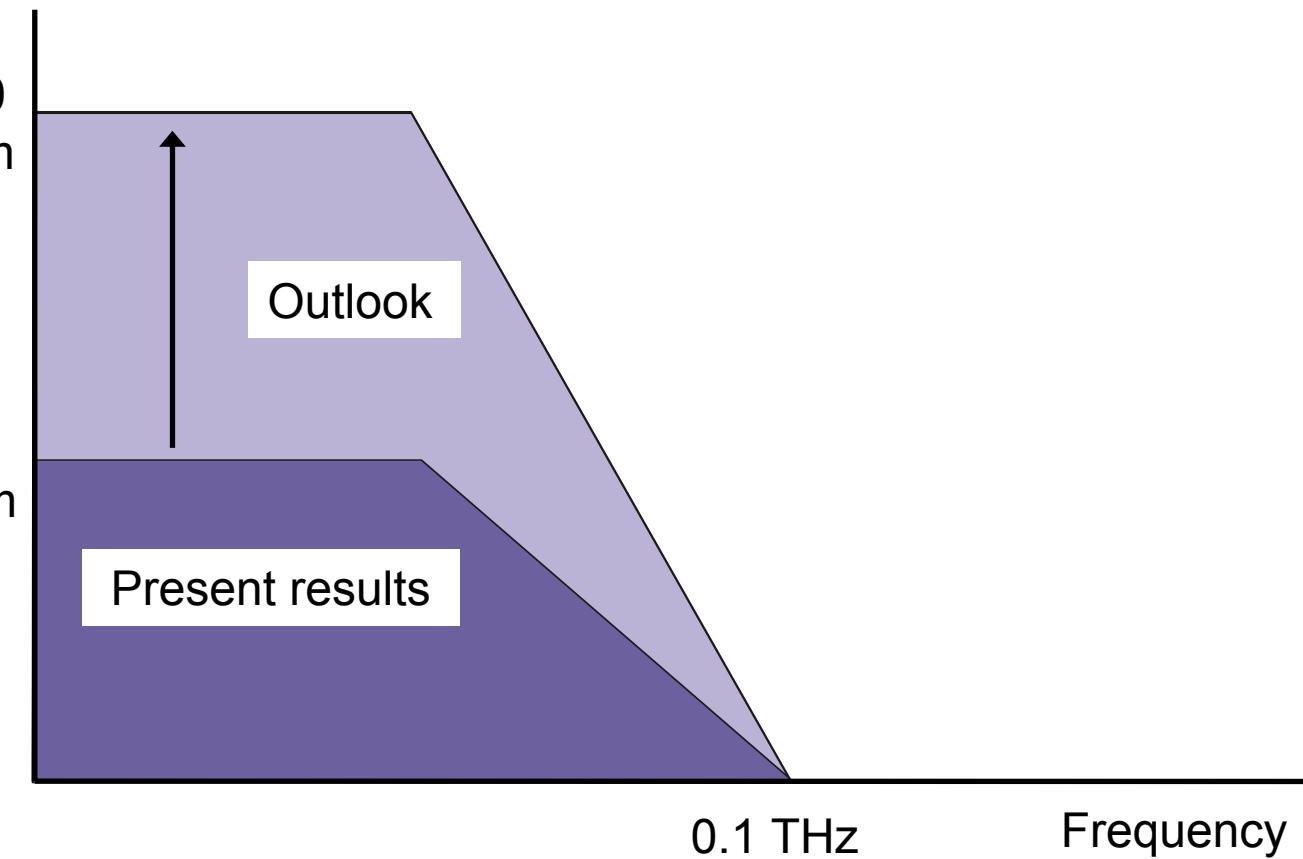
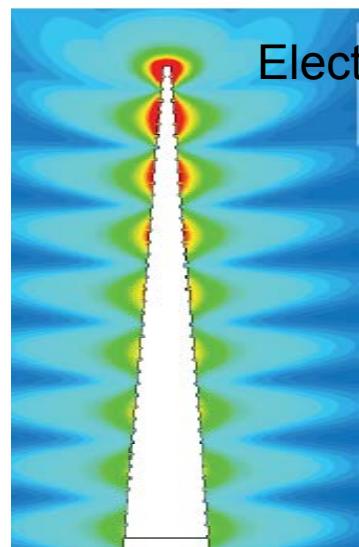
THz plasmons get dispersed & attenuated in bend, but survive!

*Field in vacuum  
at wire surface*



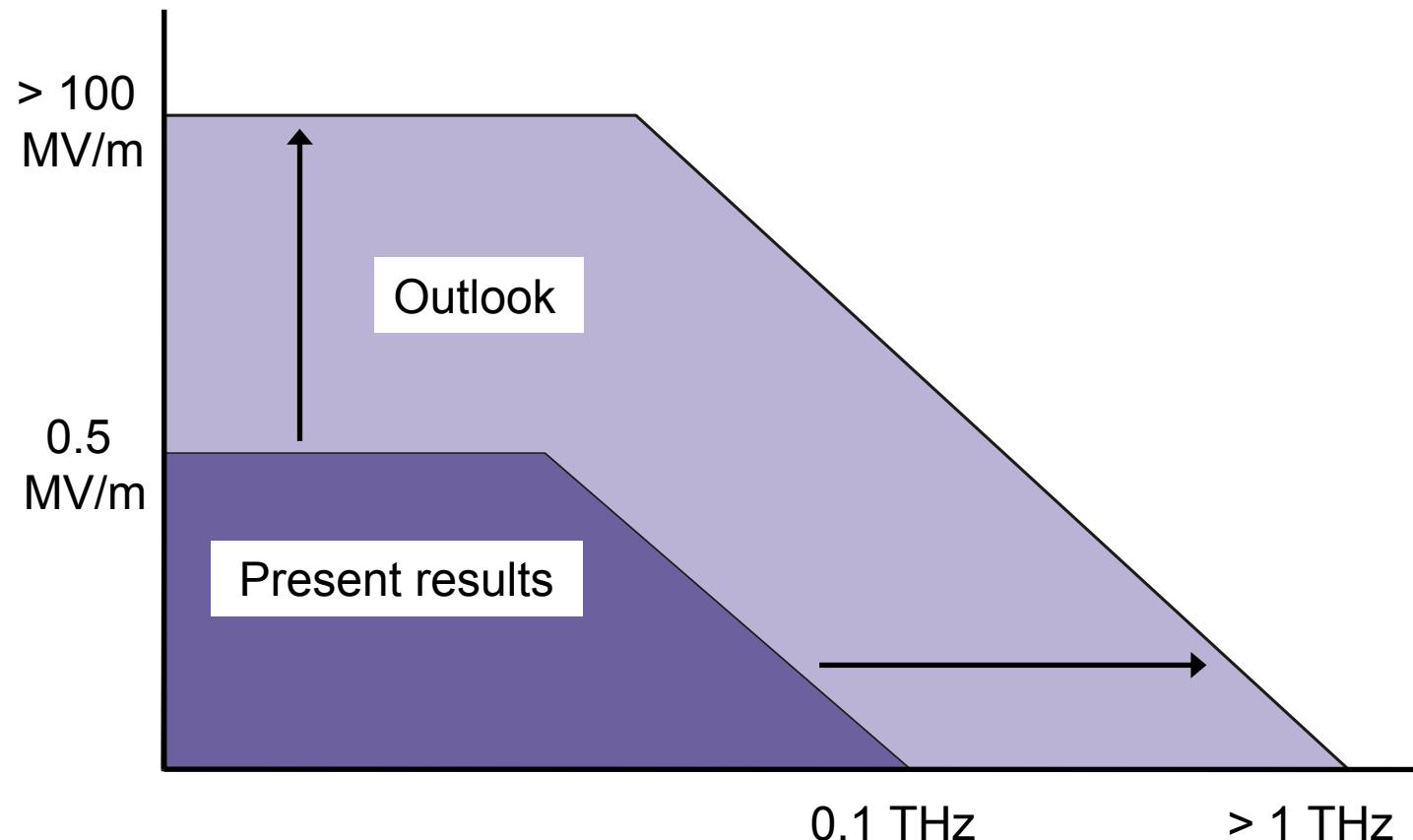
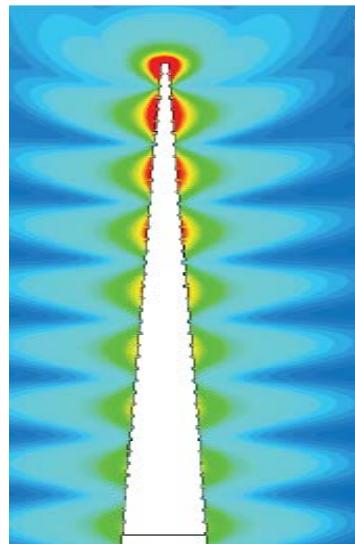
# THz surface plasmons

## Summary



# THz surface plasmons

## Summary



*Intense, broadband THz SPPs  
can be generated with an RF photogun*

